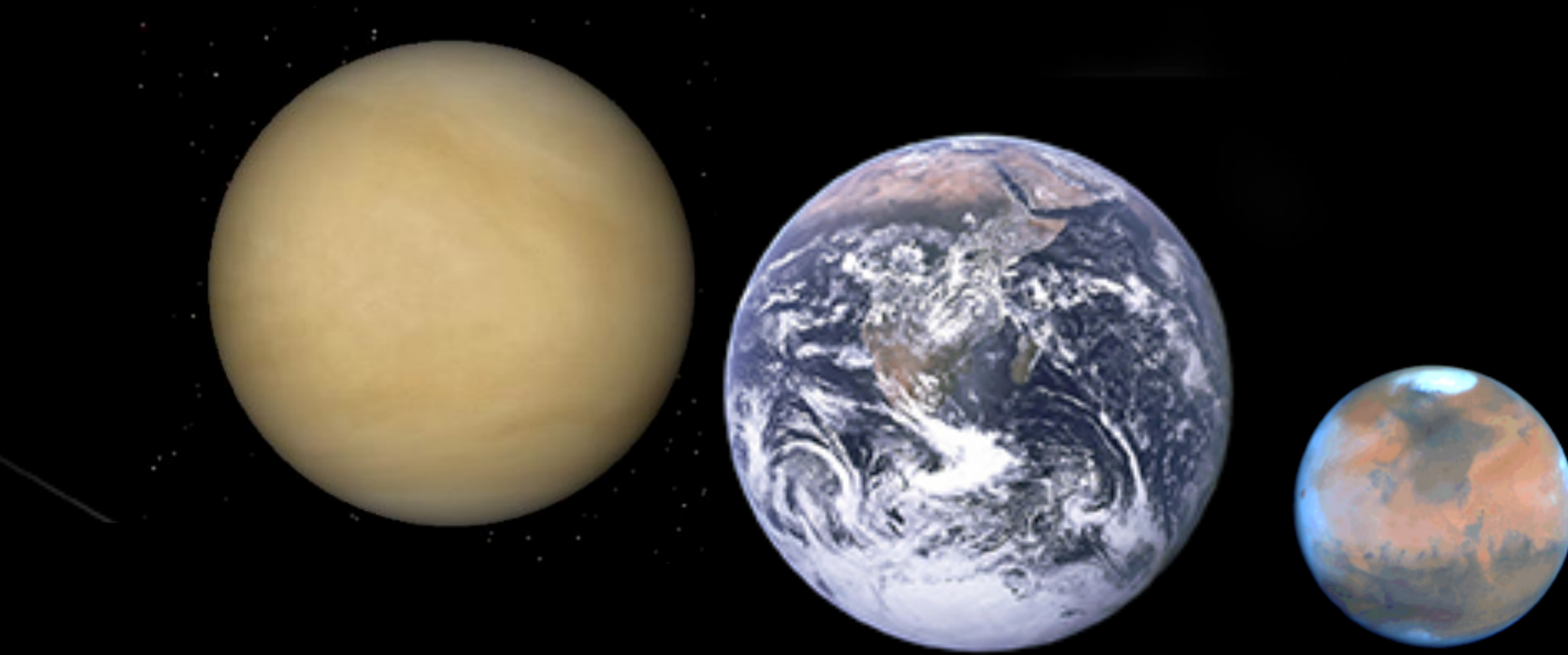
Ранние атмосферы Земли, Марса и Венеры

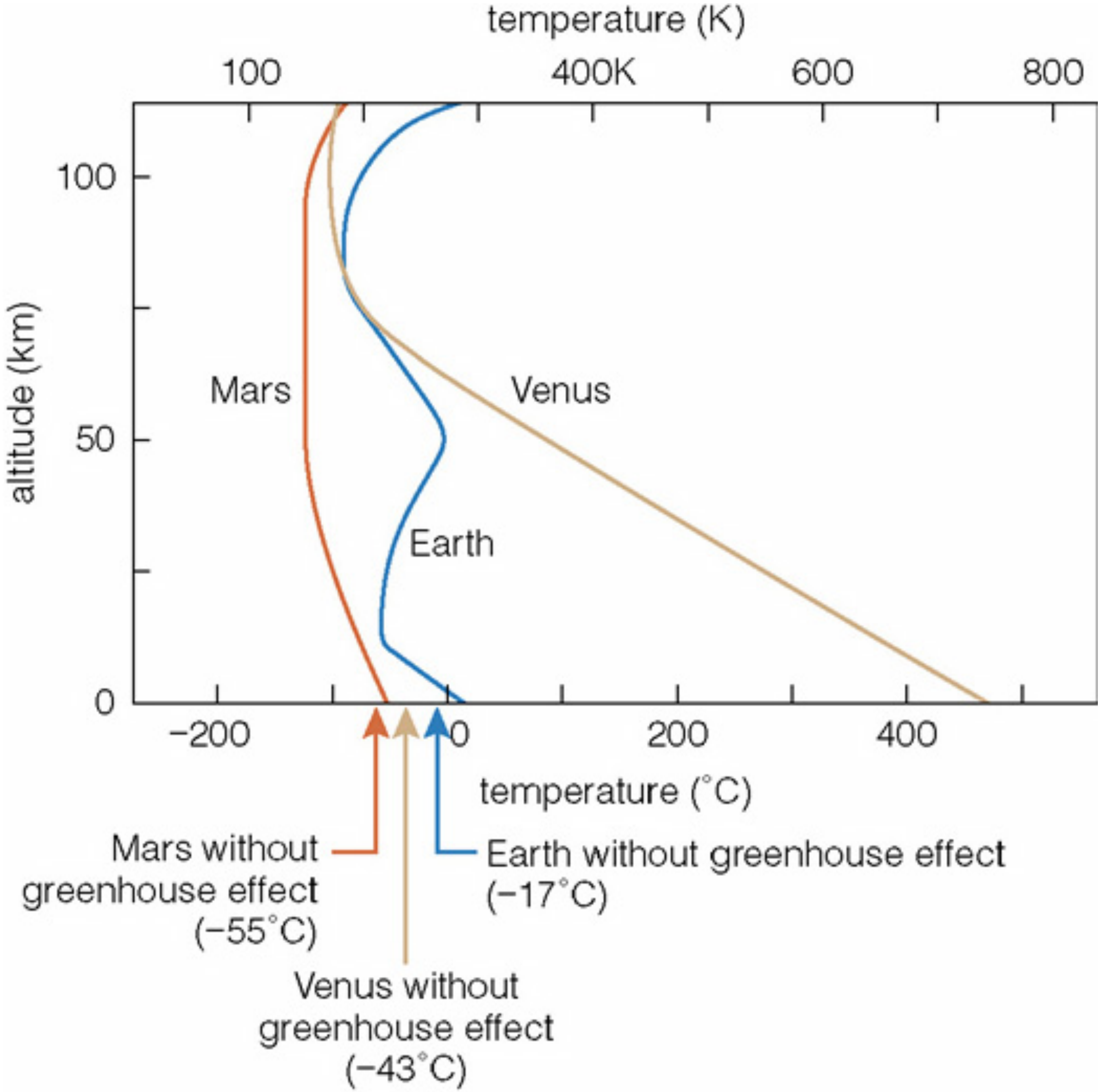
О.И. Кораблев, ИКИ РАН

Междисциплинарный коллоквиум 28-30.11.2016



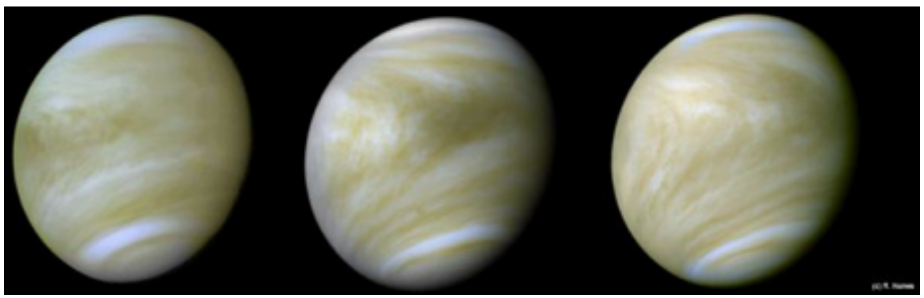
Contemporary atmospheres and climates

	Venus	Earth	Mars
Distance to the Sun, a.u.	0.72	1	1.52
Eq. radius, km	6052	6376	3380
Solar flux, W/m^2	2613	1364	589
Surface pressure, bar	92	1	0.006
Main atmospheric gases	CO_2 97% N_2 3% SO_2 0.015%	N_2 79% O_2 18% Ar 1% H_2O 2% CO_2 0.04%	CO_2 95% Ar 2% N_2 1.8% O_2 0.13%
Bond albedo	0.9	0.306	0.25
Surface temperature,°C	**462°**	14° (–90°...57°)	–63° (–140°...30°)
Greenhouse effect, K	230°	33°	3°

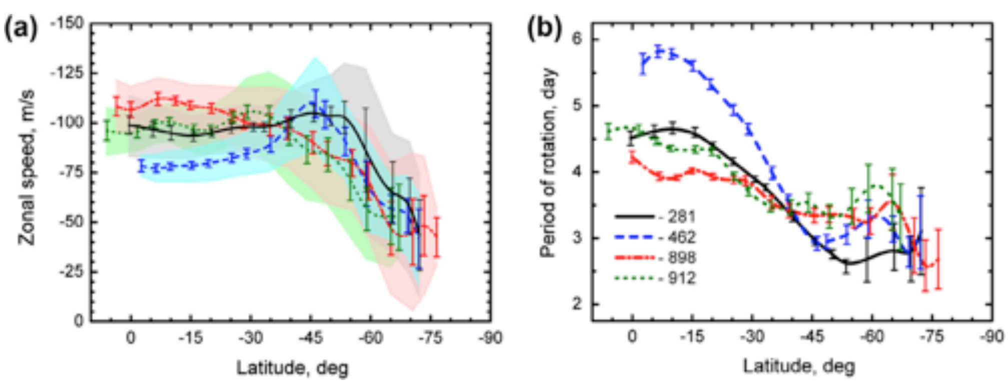

temperature (K)
100
400K
600
800
100
50
0
altitude (km)
Mars
Venus
Earth
−200
0
200
400
temperature (°C)
Mars without greenhouse effect (−55°C)
Earth without greenhouse effect (−17°C)
Venus without greenhouse effect (−43°C)

Venus ♀

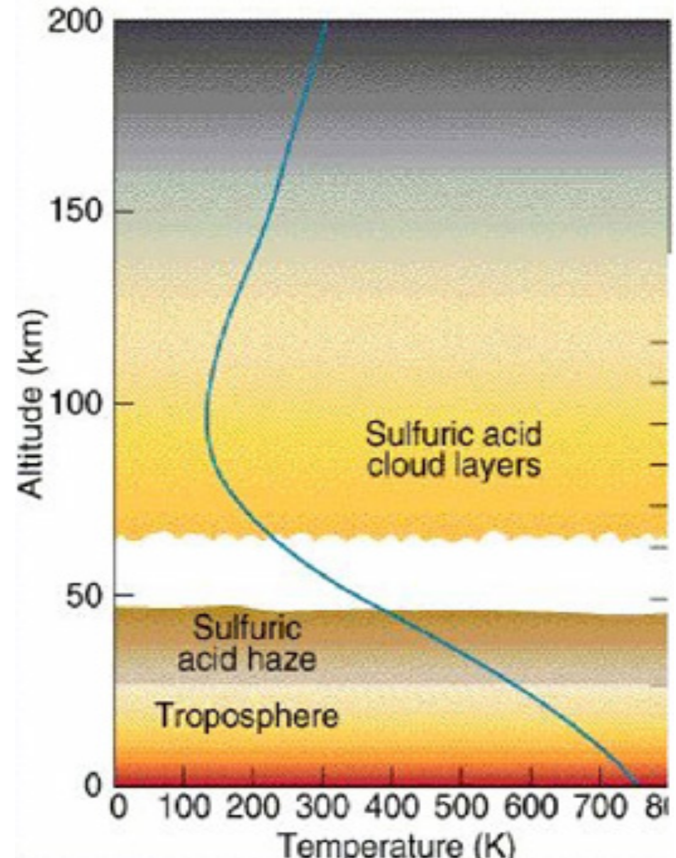
- Slow retrograde rotation
- High albedo (0.9): receives from the Sun less energy than the Earth
- Extreme greenhouse effect: CO_2+ trace water
- Dense H_2SO_4+H_2O clouds
- “No climate”, isothermal surface

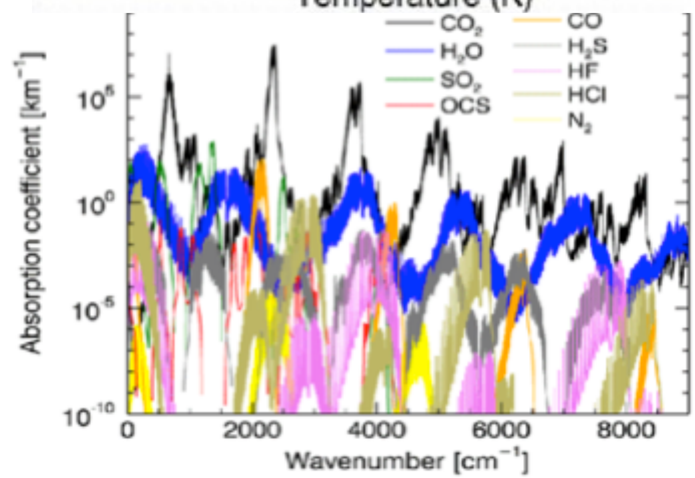


Superrotation: Detecting the cloud motions



Wind speed and superrotation period [Khatuntsev et al., 2013]

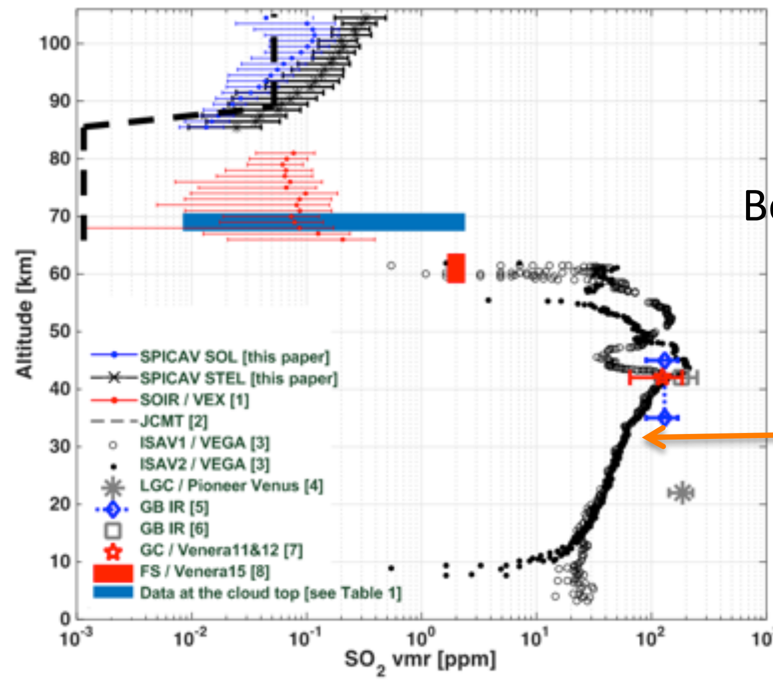




Absorption by different gases at 40 km [Lee et al., 2016]

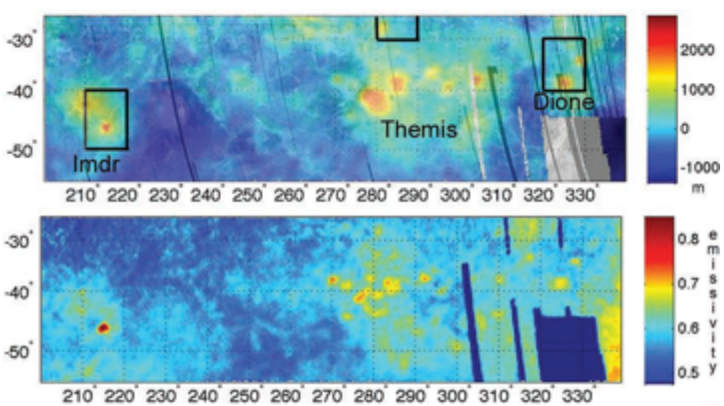
Venus atmosphere: Unsolved problems

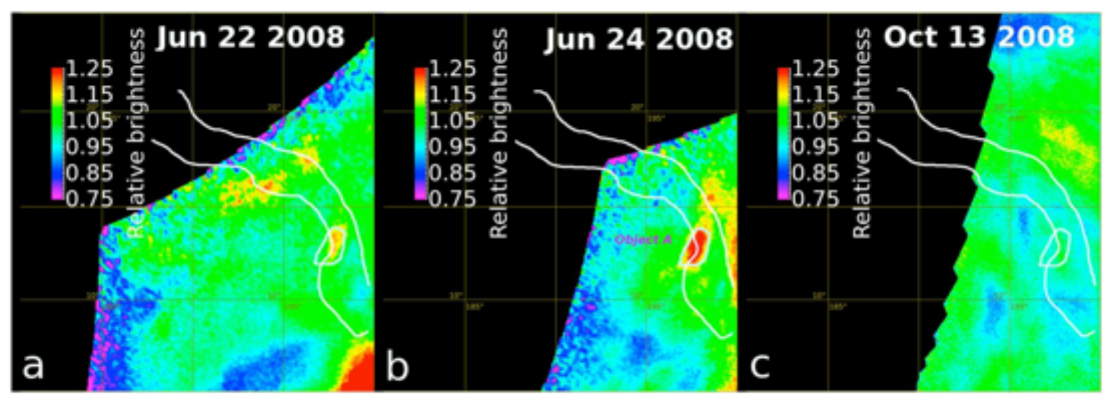
- Chemistry of the lower atmosphere
- Modern volcanism
- Long-term trends



Belyaev et al., in prep [ISSI Team]

VeGa SO_2, profile [Bertaux et al., 1996]



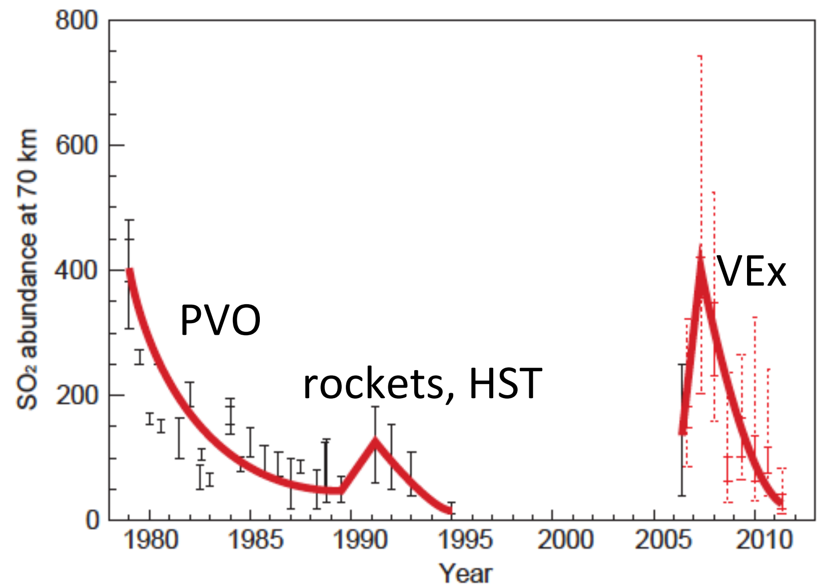


1.06 µm emissivity VIRTIS/Venus Express [Smrekar et al. Sci 2010; Shalygin et al., GRL 2015]

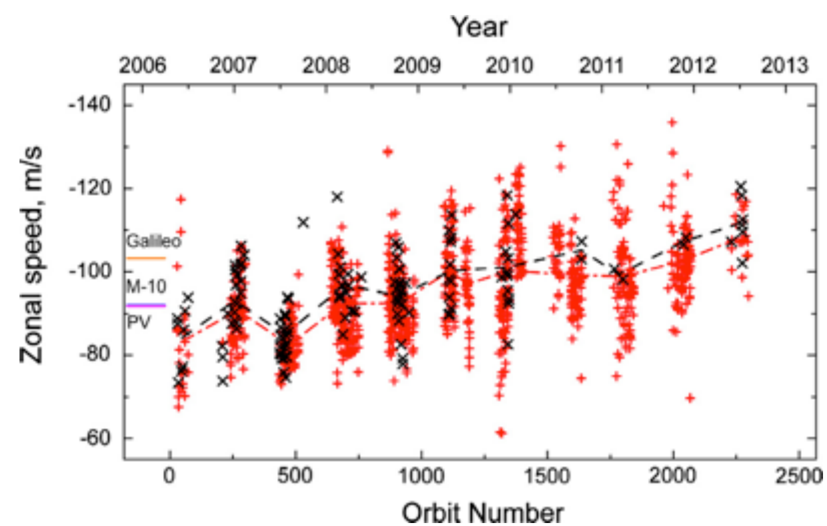
Short-term climate changes on Venus

- All atmosphere profiles from descent probes coincide
- Two long data series
  - Pioneer Venus Orbiter (1978-1992)
  - Venus Express (2006-2014)
- Observed SO_2 variations may be connected to volcanic activity (Esposito et al., Sci 1984)

- Apparent increase of zonal wind speed recognized as effect of observational selection



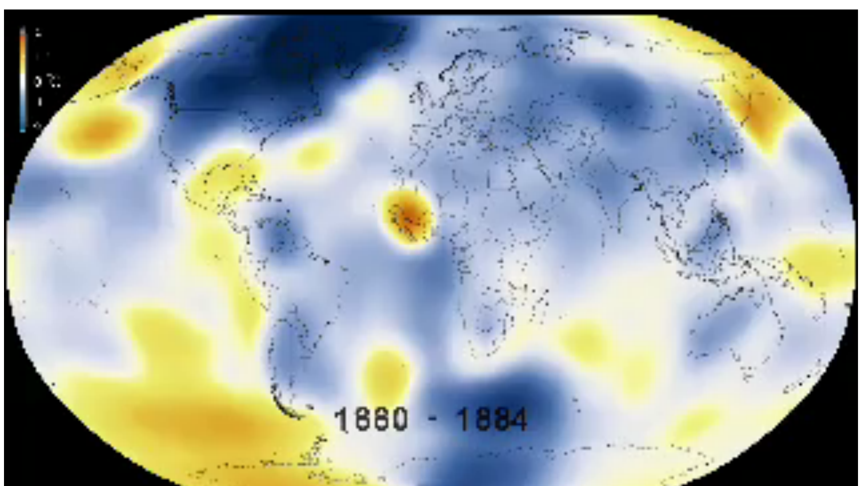
after Marcq et al., NatGeo 2013



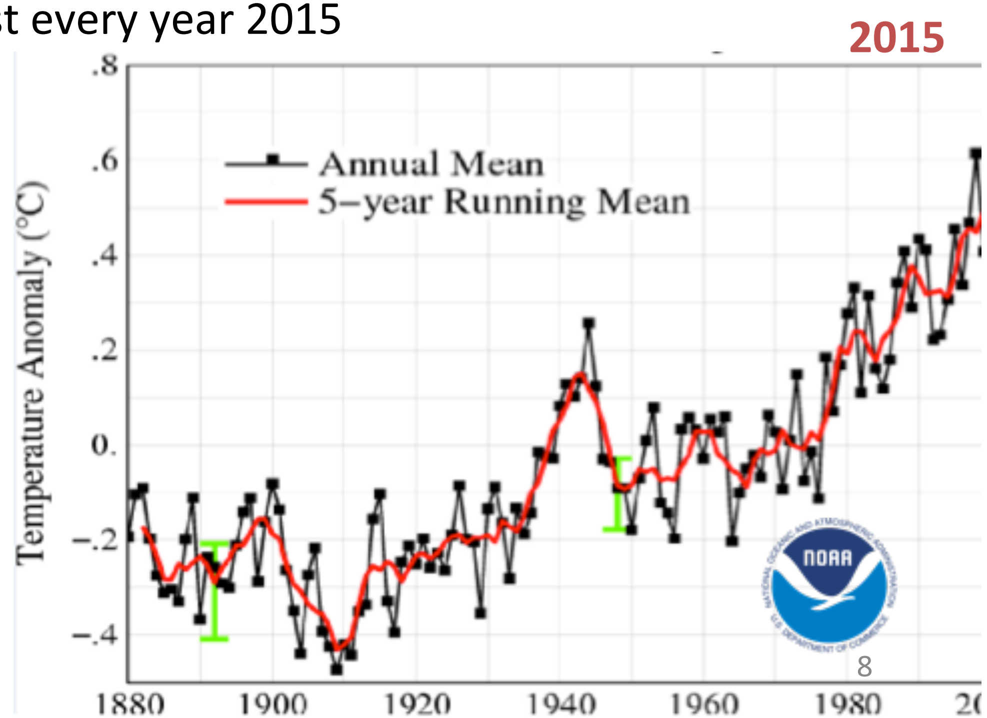
Venus Express: Khatuntsev et al., 2013

Earth: Global warming

- Antropocen (E.F. Stoermer, P.J. Crutzen)
  - Industrial revolution in 18 century
  - Now the Earth population is 7.4 10^9 people .
  - 2050 → ~10^{10} (75% urban)
- Global warming
  - CO_2 rise (400 ppm now)
  - Maximal temperature grow almost every year 2015



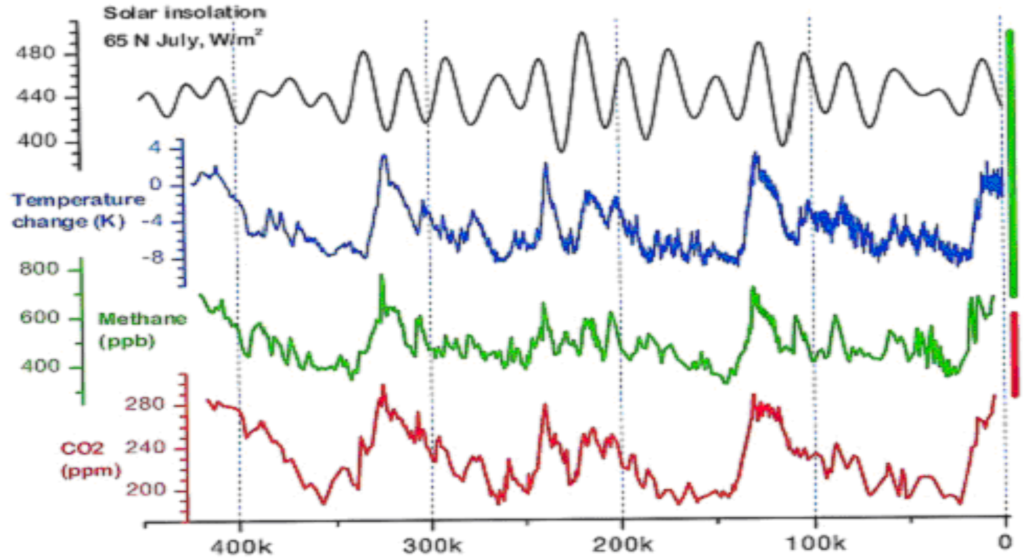
NASA/GISS



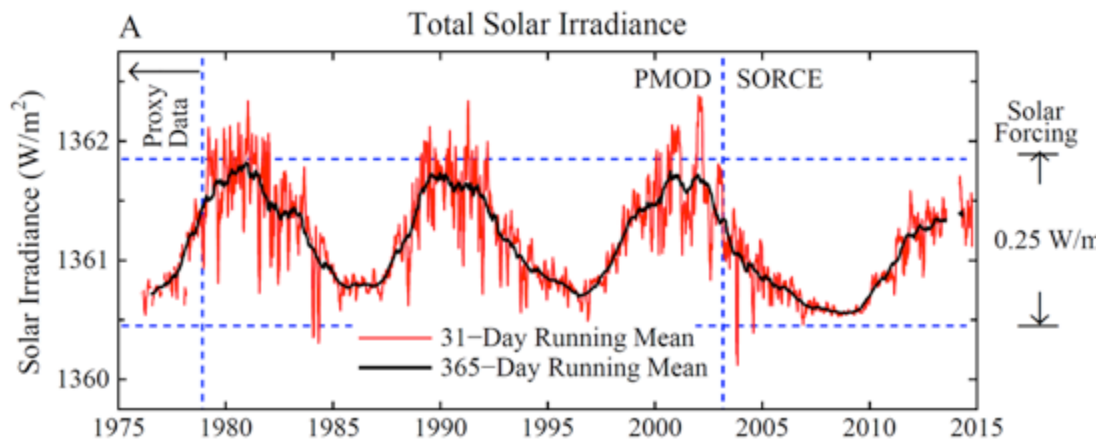
Global changes on Earth

- Paleoclimate records for 650 ky: temperature change within 10°C, CO_2<300 ppm
- Milankowich cycles
  - Precession 27 ky
  - Obliquity change (41 ky)
  - Eccentricity change (100 ky)
- Nonlinear feedback (Ocean!) и комбинации циклов
- Ice ages repeating after 100 or 41 ky
- Climate change on smaller scales downto ~1500 y

- Solar influence?? (~0.1 %)



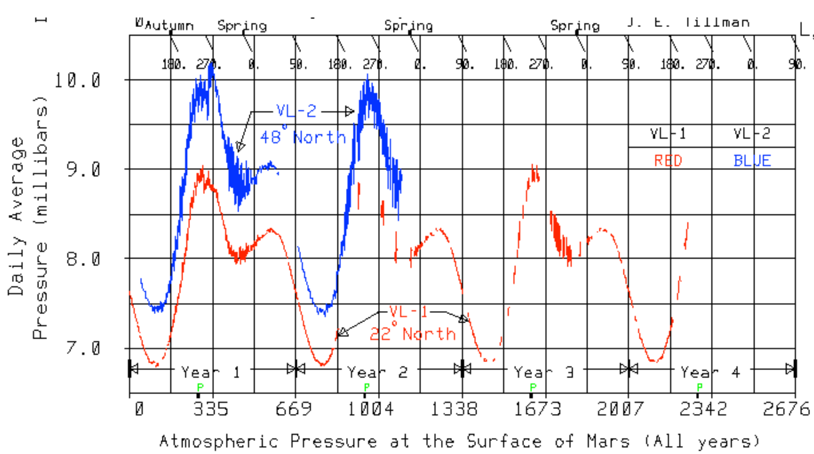
Vostok lake ice records

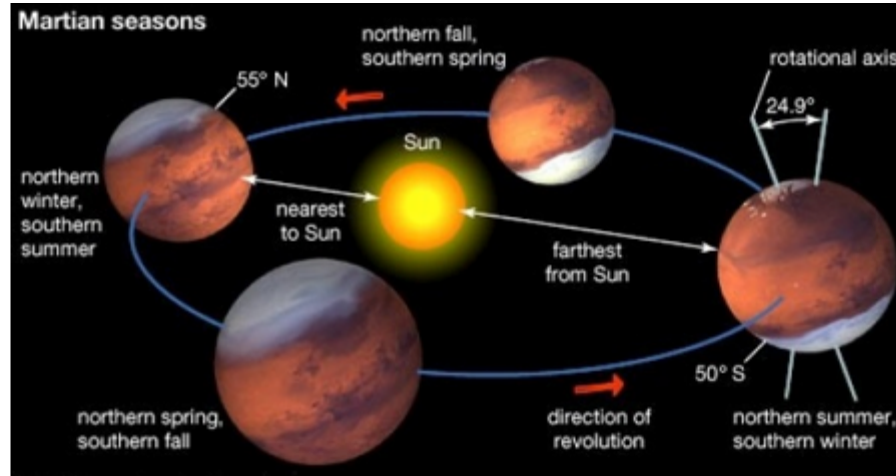


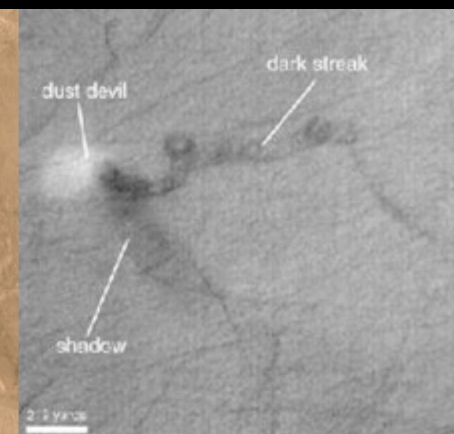
Mars ♂

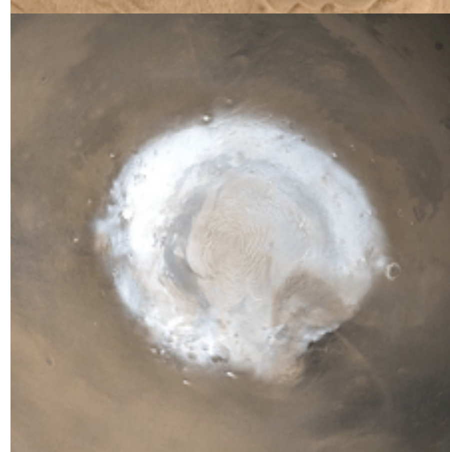
- Pronounced seasonal cycle
- Mean pressure (6 mbar) close to water triple point
- Condensation of CO_2 in polar regions in winter
- Ubiquitous atmospheric dust; Global dust storms

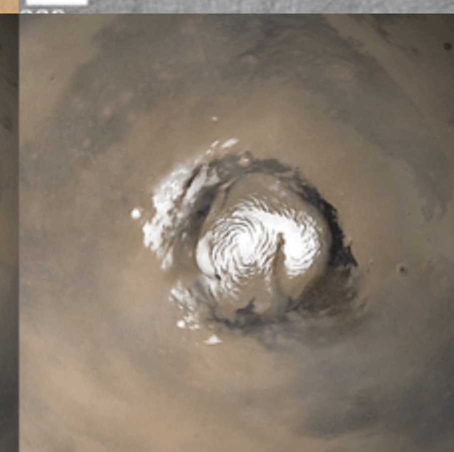
- No active volcanism detected









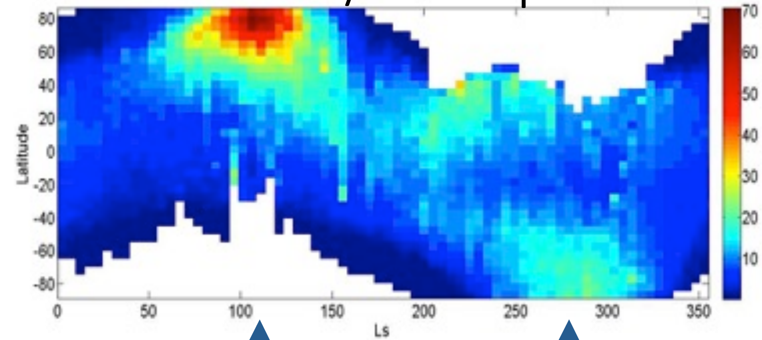


Mars: Water inventory

- Atmosphere: 10-20 µm
- Polar caps ~20 m of Global Equivalent Layer
- Neutron data (depth 1-2 m): 14 cm
- Radar data (depth <2.5 km): ~11 m

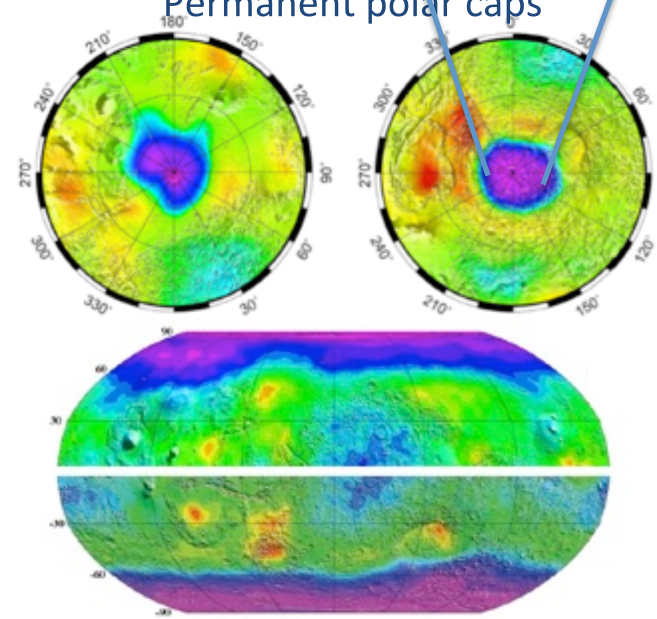
Total estimate ≥30 m (Lasue et al. SSRv 2013)

SPICAM/Mars Express

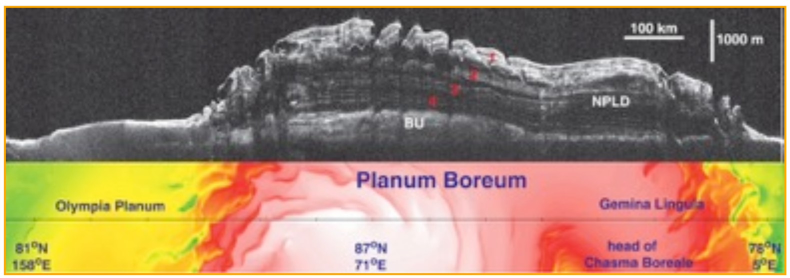


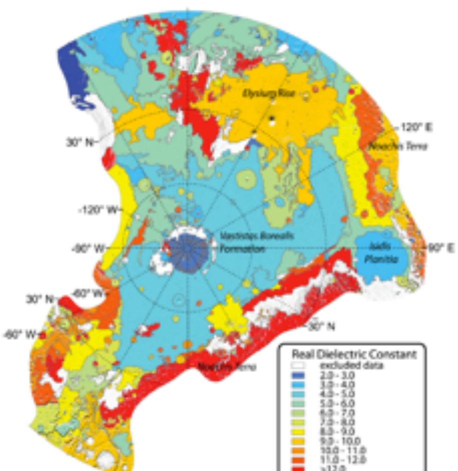
Season: Northern summer (aphelion) Southern summer (перихелион)

Permanent polar caps



GRS and HEND/Mars Odyssey



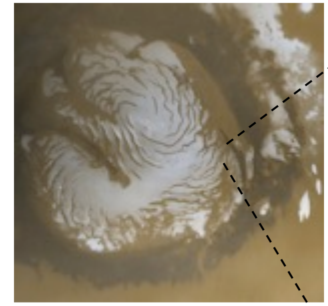


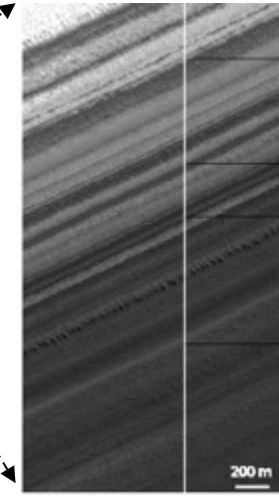
MARSIS/Mars Express

Mars obliquity and climate change

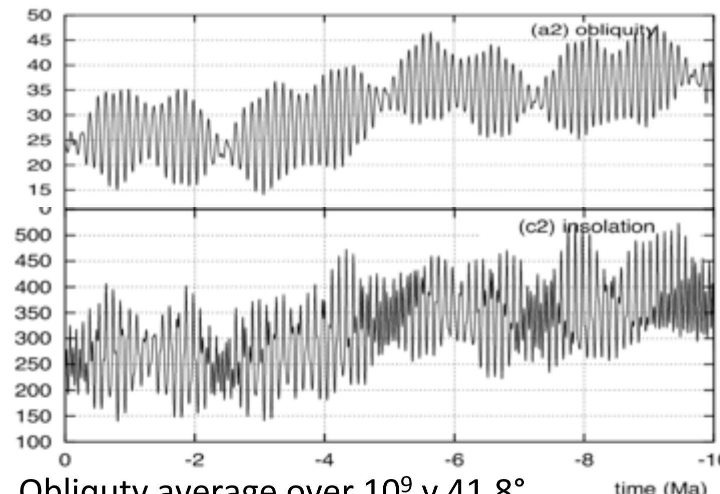
- Change of precession, axis tilt and orbit eccentricity
- Polar Layered Deposits
- Low latitude glaciations (> 40 mln. y)
- Average period of ice accumulation ~50 000 y (precession is the fastest cycle)

Montmessin SSRv 2005 [ISSI 2004 workshop]

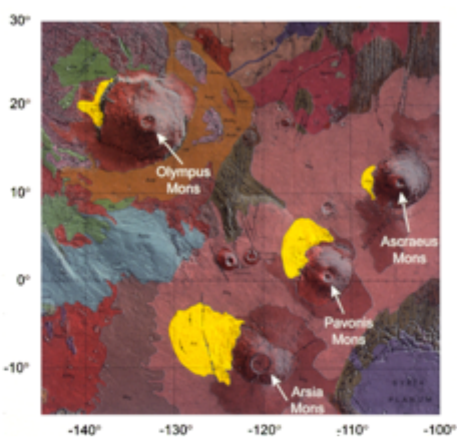




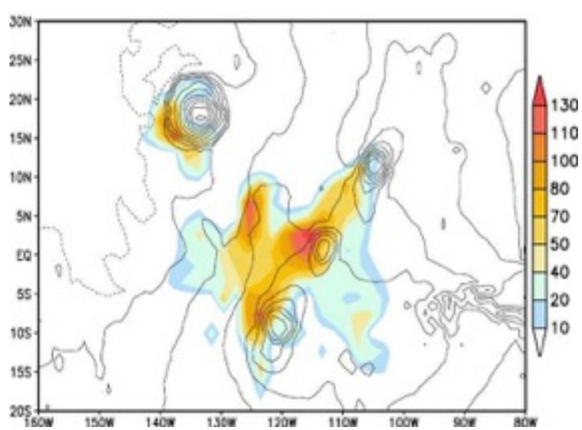
[Milkovich & Head JGR, 2005]



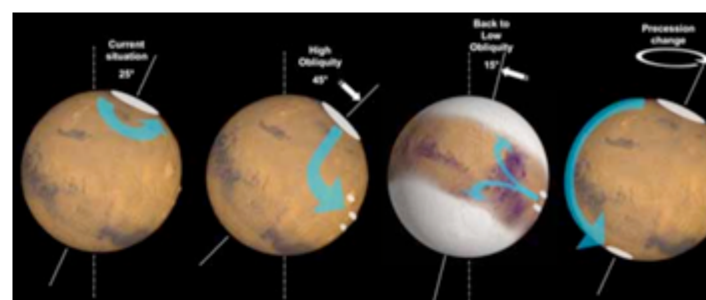
Obliquty average over 10^9 y 41.8°
[Laskar et al., 2004]



Geologic mapping
[Head et al. 2005]



GCM: precipitation at ~40° obliquity
[Levrard et al. 2007]

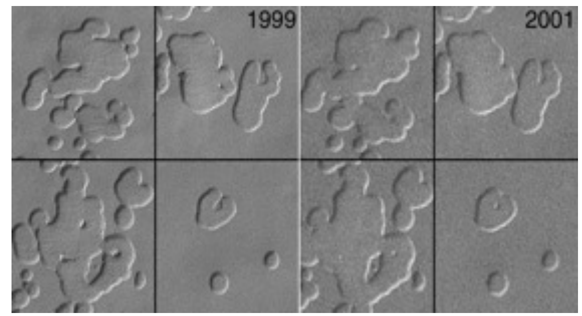


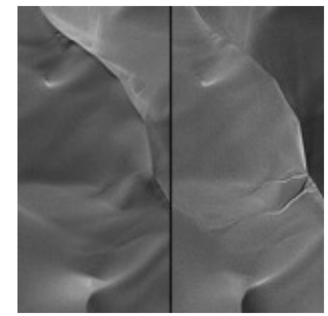
[Head et al. 2003]

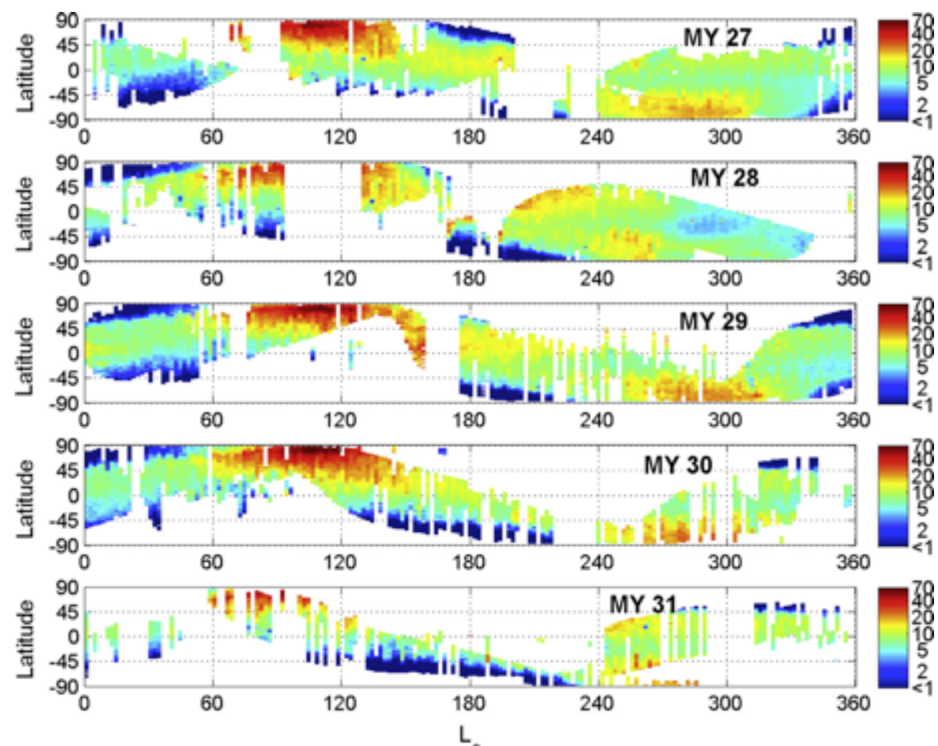
Mars: Short-term climate change?

- Mars Global Surveyor
  - "Swiss cheese" [e.g. Byrne&Ingersoll GRL 2003]
  - New gullies
- Albedo change MGS (1997-2004) vs Viking (1976-1980) ➔ warming of 0.6-0.8 K
- Water vapor in the atmosphere

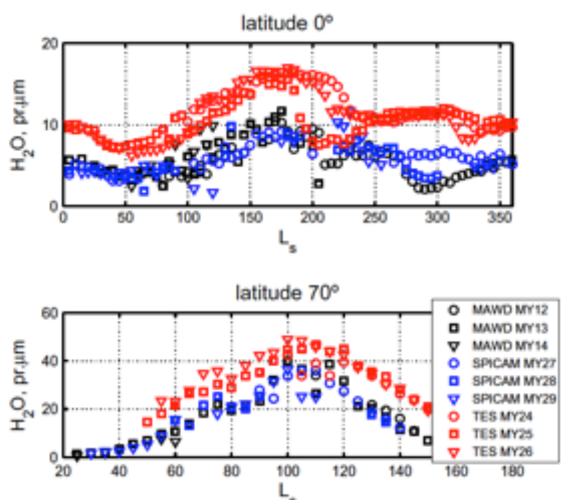
1) MGS vs Viking ➔ cooling
2) Mars Express vs Viking: **No change** [ISSI Team]







SPICAM/Mars Express: [Trokhimovsky et al., 2015]



SPICAM&Viking vs TES [Fedorova et al., 2010]

Ранние атмосферы

Timescale	Accumulation	Losses
0-10 ky	Capture and accumulation of gasses from the planetary nebula	-
10ky-10My	Catastrophic outgassing due to magma ocean solidification	Hydrodynamic escape
??-0.6 My 4.1-3.8 Ga (LHB)	Volatile delivery by impacts	Ejection ?
4.? Ga- now	Degassing by volcanic processes	Preferential escape

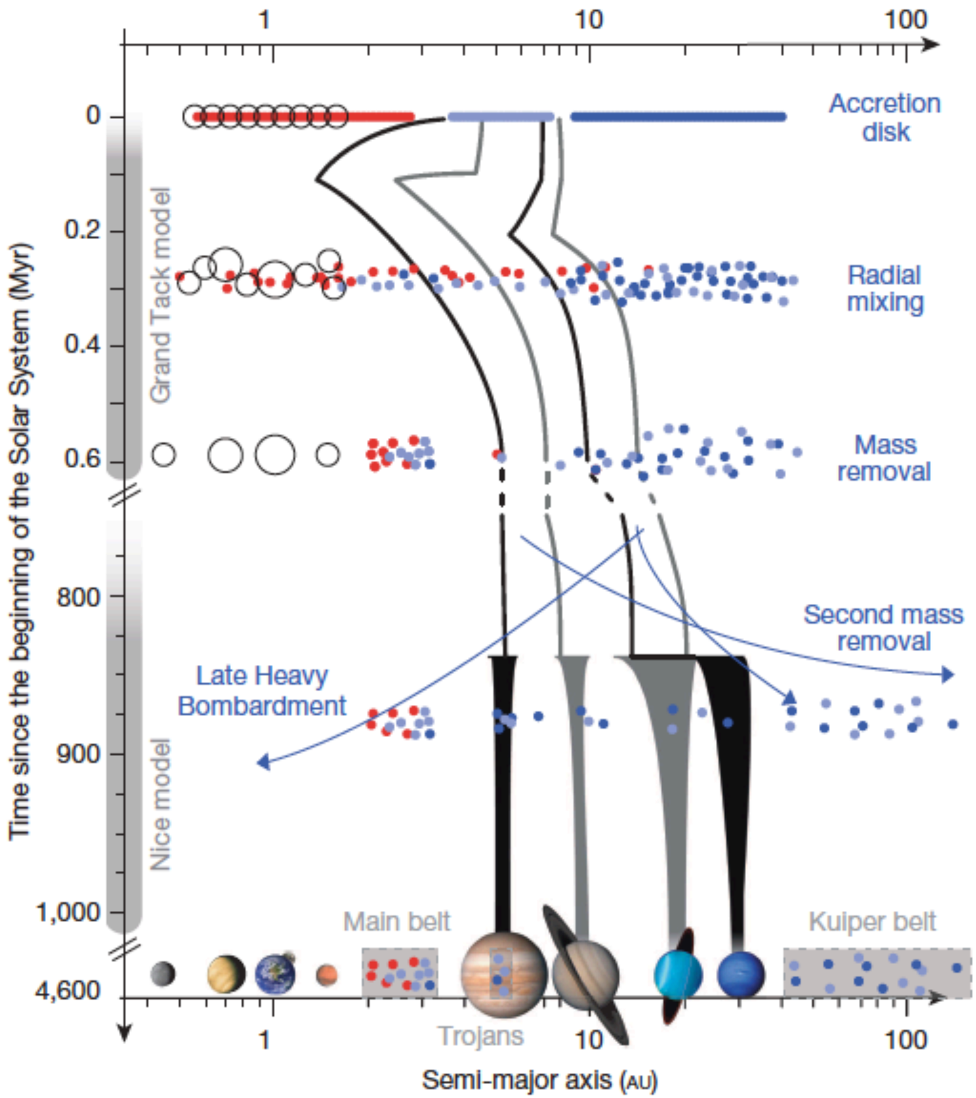


Figure 2 | Cartoon of the effects of planetary migration on the asteroid belt. This figure captures some major components of the dynamical history of small bodies in the Solar System based on models[11,12,51,54]. These models may not represent the actual history of the Solar System, but are possible histories. They contain periods of radial mixing, mass removal and planet migration—ultimately arriving at the current distribution of planets and small-body populations.

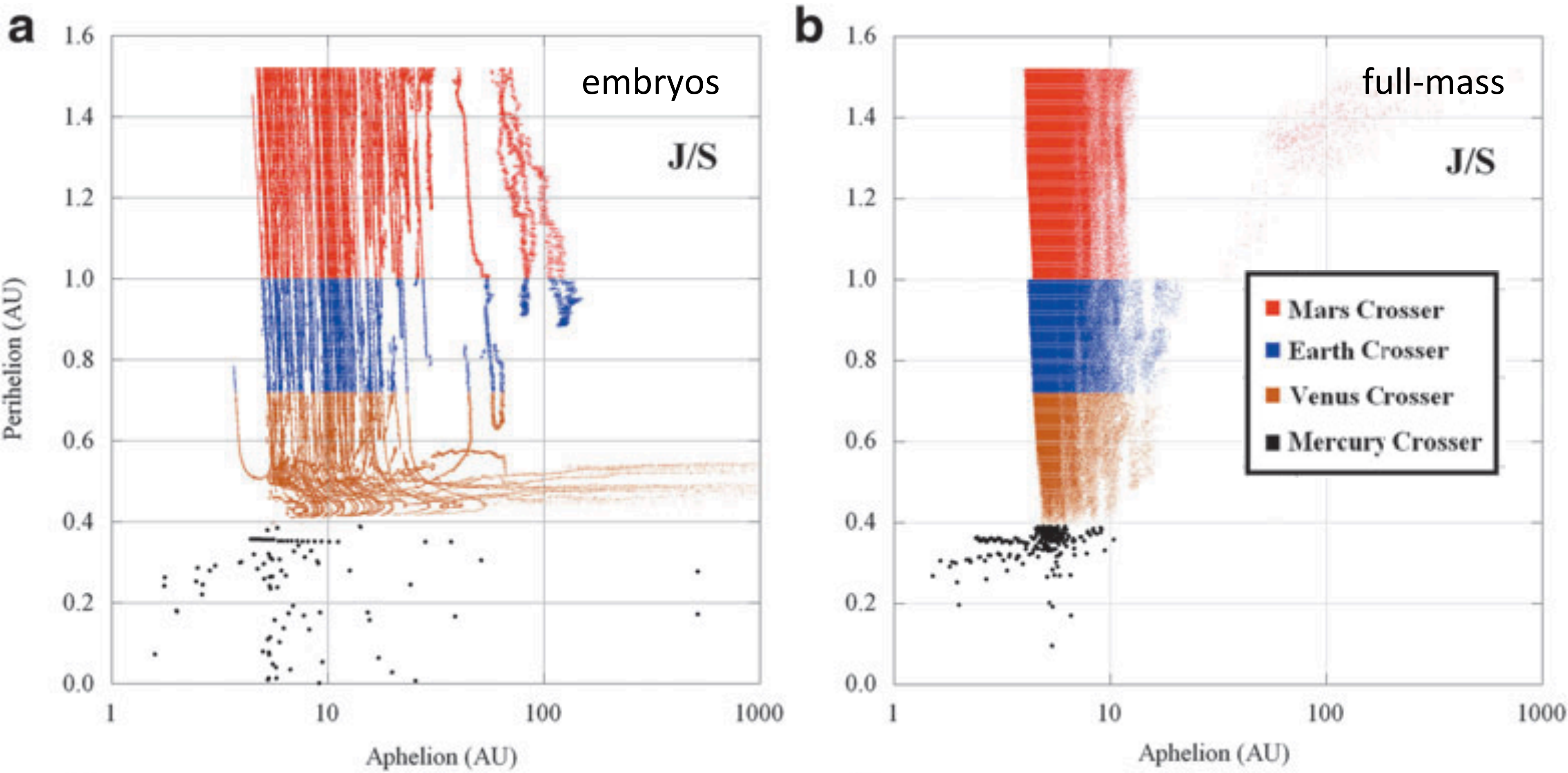
DeMeo and Carry, Nature 2014

Timescales

Grand Tack scenario: Jupiter's early gas-driven migration
Walsh et al. Nature (2011)
Alternative:
Terrestrial planet formation from a narrow annulus
Hansen ApJ (2009)

Nice model: Migration of giant planets long after the dissipation of the initial protoplanetary gas disk.
Tsiganis et al., Nature 2005

Jupiter+Saturn



Fate of planetesimals orbiting in the outer Solar System in the presence of full-mass jovian planets and their embryos

Grazier AsBio 2016

Океаны магмы

- Разогрев при аккреции и, в дальнейшем, из-за метеоритных ударов
- Разогрев из-за экранирования атмосферой

- Models indicate that with very small initial volatile contents (<1 % weight), solidification of one partial mantle magma ocean can produce significant atmospheres (100-1000 bars H_2O+CO_2)
- Super-critical point of water temperatures are reached within tens of millions of years
- When the surface temperature cools below the critical point (approximately 647 K and 220 bars) the supercritical fluid and steam atmosphere collapse into an ocean.

22

Earth and Planetary Science Letters, 43 (1979) 22–28

[6]

EARTH'S MELTING DUE TO THE BLANKETING EFFECT OF THE PRIMORDIAL DENSE ATMOSPHERE

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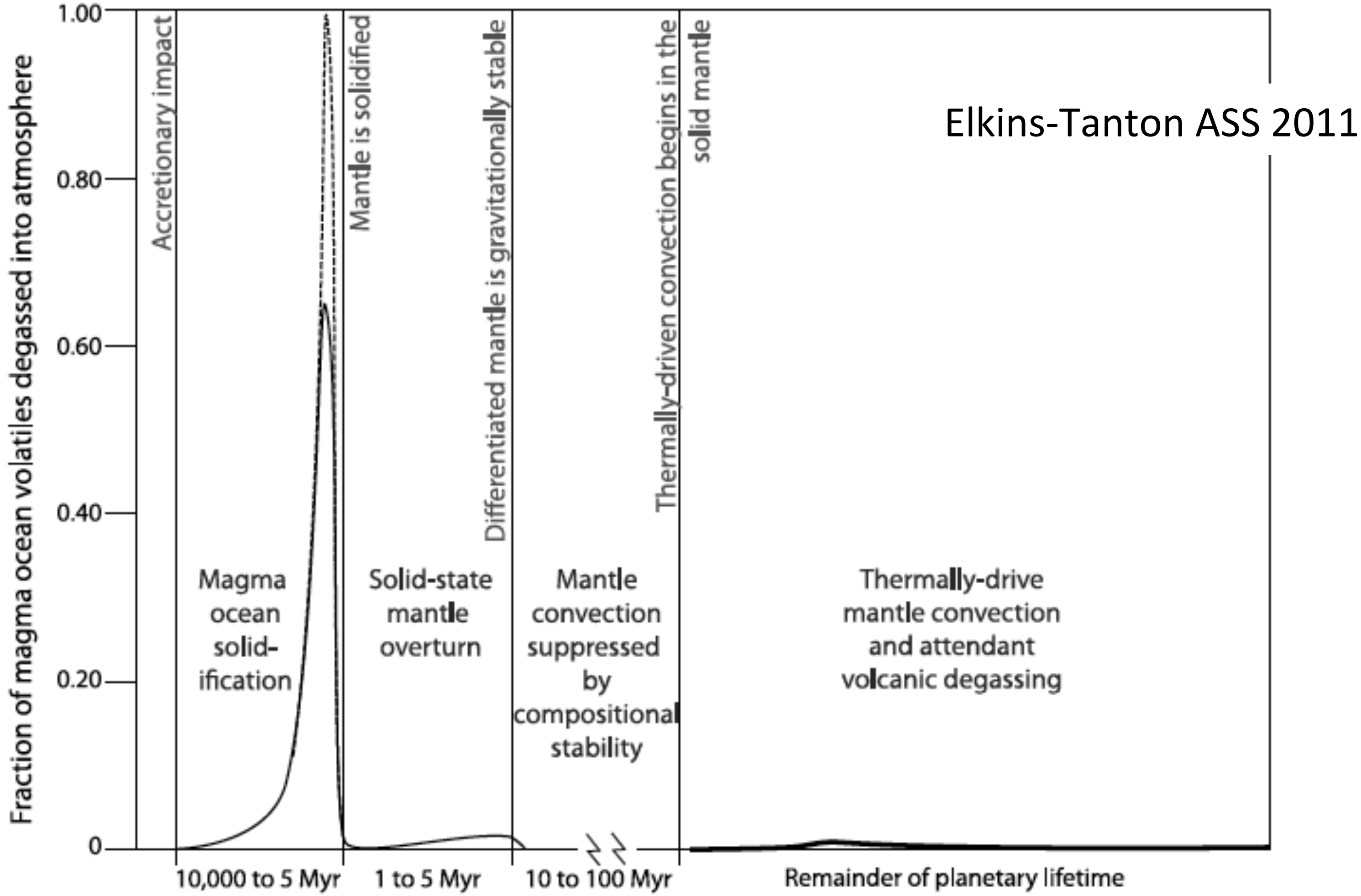


Fig. 4 Schematic timeline of planetary degassing into oceans and atmospheres. The *vertical axis* represents the fraction of volatiles present in the magma ocean before solidification begins that are degassed (1 = all initial volatiles degassed; none remaining in planetary interior). The *bold solid line* represents larger planets and lower initial volatile contents in magma oceans (0.01 mass% or less), while the *bold dashed line* represents smaller planets and higher initial volatile magma oceans (see Table 3 in Elkins-Tanton 2008). The time to magma ocean solidification depends primarily upon initial volatile content, which along with planetary mass controls the time required for solid-state mantle overturn—a process driven by density gradients within the solid mantle following the magma ocean stage (Solomatov 2000; Elkins-Tanton 2008)—and the length of mantle convection suppression that follows overturn to stability. By far the greatest fraction of volatiles are released onto the planetary surface during solidification

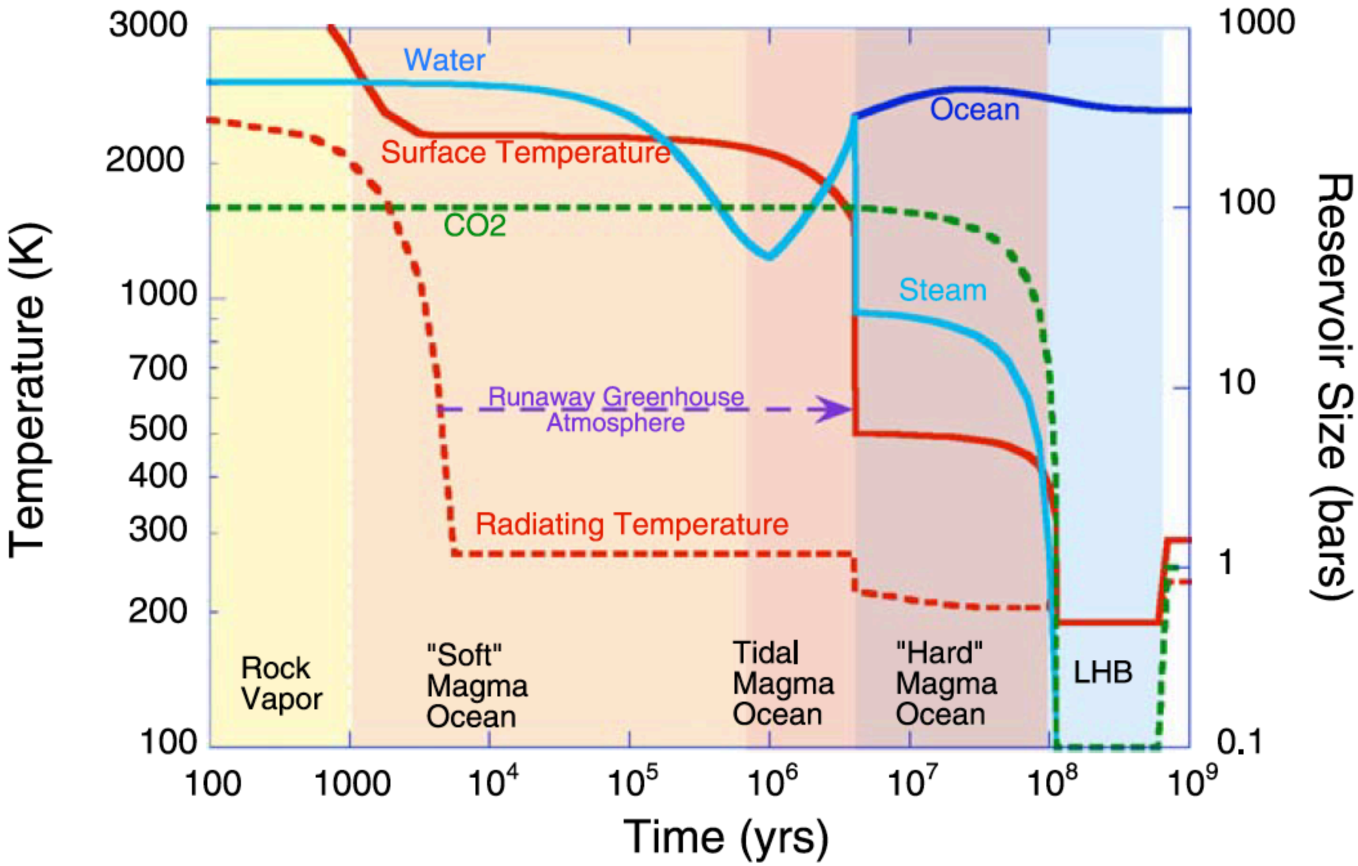


Fig. 5 A cartoon history of temperature, water, and CO_2 during the Hadean. The Hadean begins with the Moon-forming impact. For 1,000 years Earth is enveloped in rock vapor. CO_2 and other gases are presumed to degas from the convecting silicate gas, while water mostly partitions into the interior. A substantial greenhouse effect and tidal heating maintain the magma ocean for some 2 million years. Most of Earth's water and the rest of the CO_2 degassed as the mantle solidified. After the mantle solidified the steam atmosphere condensed to form a warm (∼500 K) water ocean under ∼100 bars of CO_2. This warm, wet early Earth would have lasted while Earth's CO_2 stayed in the atmosphere. In this illustration CO_2 is assumed to subduct into the mantle on either a 10 Myr (*solid curves*) or a 100 Myr (*dotted curves*) time scale. The asymptotic CO_2 partial pressure is assumed to be controlled at low levels by chemical weathering of oceanic crust and abundant ultramafic impact ejecta. Prior to the origin of life, in the absence of an abundant potent greenhouse gas, the surface should have been ice covered and very cold, although occasional impacts brought brief thaws. Finally, after the late bombardment, the CO_2 is allowed to return to ∼1 bar levels in order that the surface be clement; this too is arbitrary

Zahnle et al. SSRv 2006

Состав ранней атмосферы

- Accreted atmosphere (similar to Jupiter, Saturn, Uranus, and Neptune): H_2, He_2 + simple hydrides (H_2O, CH_4, NH_3)

Hayashi et al. 1979; Lewis &Prinn 1984; Ikoma & Genda 2006

- Secondary atmosphere (similar to volcanic gases): H_2O, CO_2, and N_2 + little CO and H_2

Holland 1962; Abelson 1966; Holland 1984

  – Alternative: Reducing atmosphere

Urey 195x

Zahnle et al. 2010

Noble gases

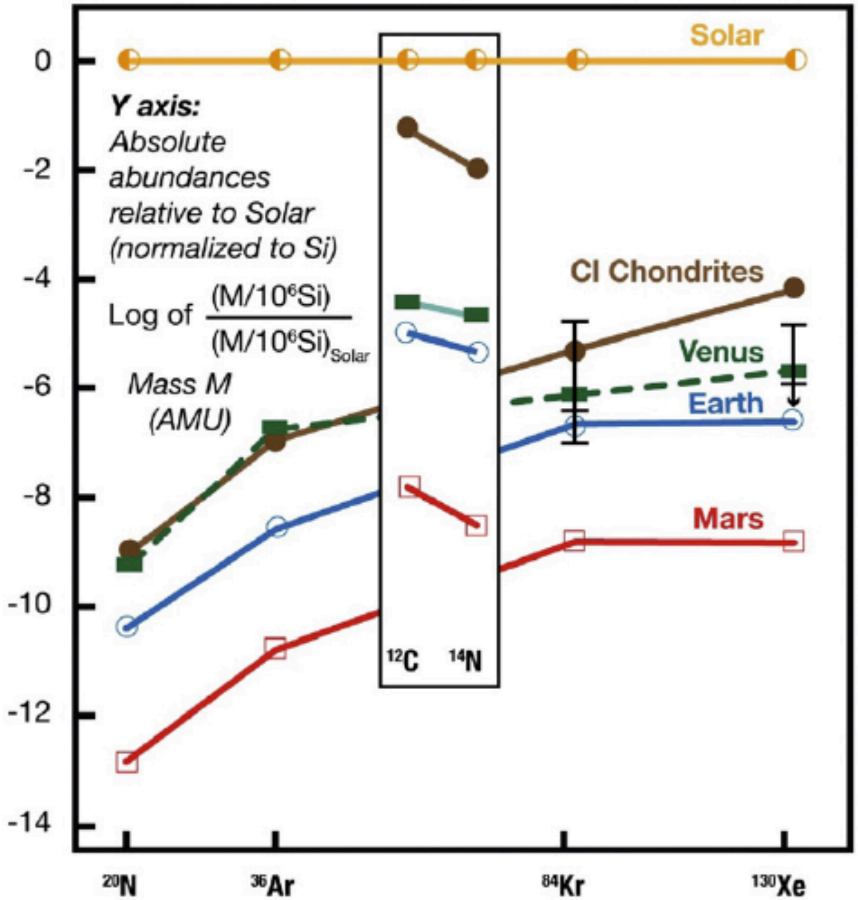
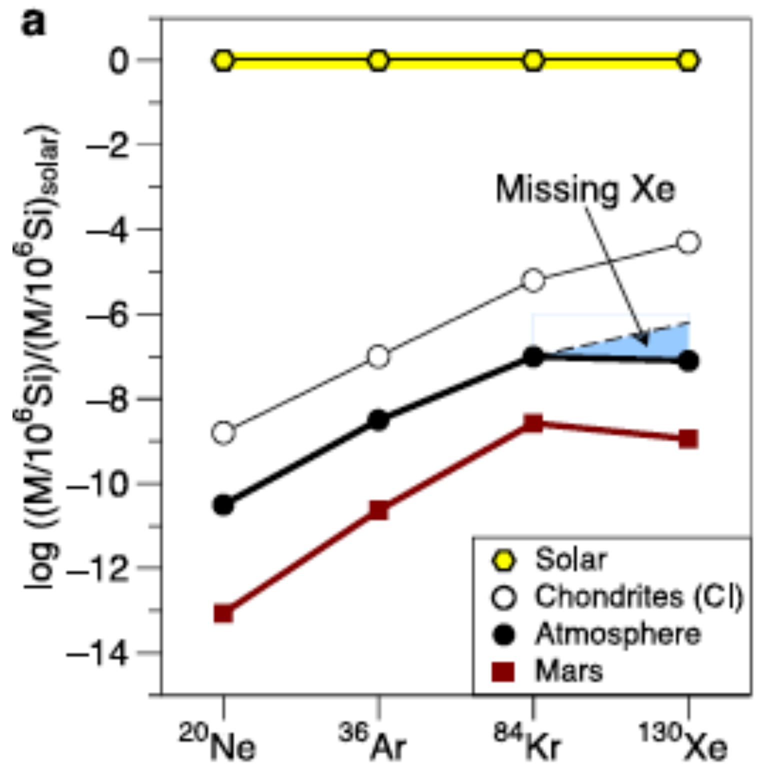


Fig. 3. Concentrations of the four heavier noble gases in the atmospheres of the three major terrestrial planets normalized to the rock-forming element Si and to solar composition (figure reworked by T. Balint after Pepin, 1991). Also shown are the data of the chemically most-primitive meteorites, the CI chondrites, which might serve as a possible analog of planetary building blocks. The uncertainties on the abundances of Kr and Xe are of nearly one order of magnitude.

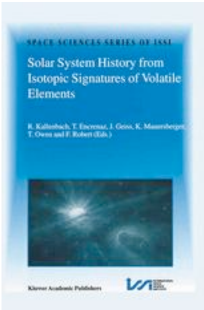
- Mars: Viking Landers, Mars meteorites
- Venus: Pioneer Venus

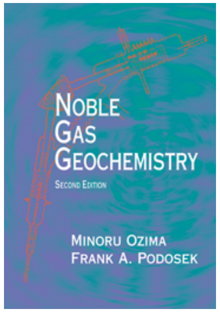


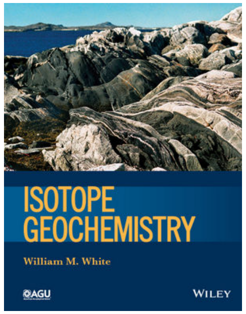
Pepin, Icarus 1991; Mousis et al., ApJ 2010; Lammer et al., SSRv 2013; Marty et al., EPSL 2016

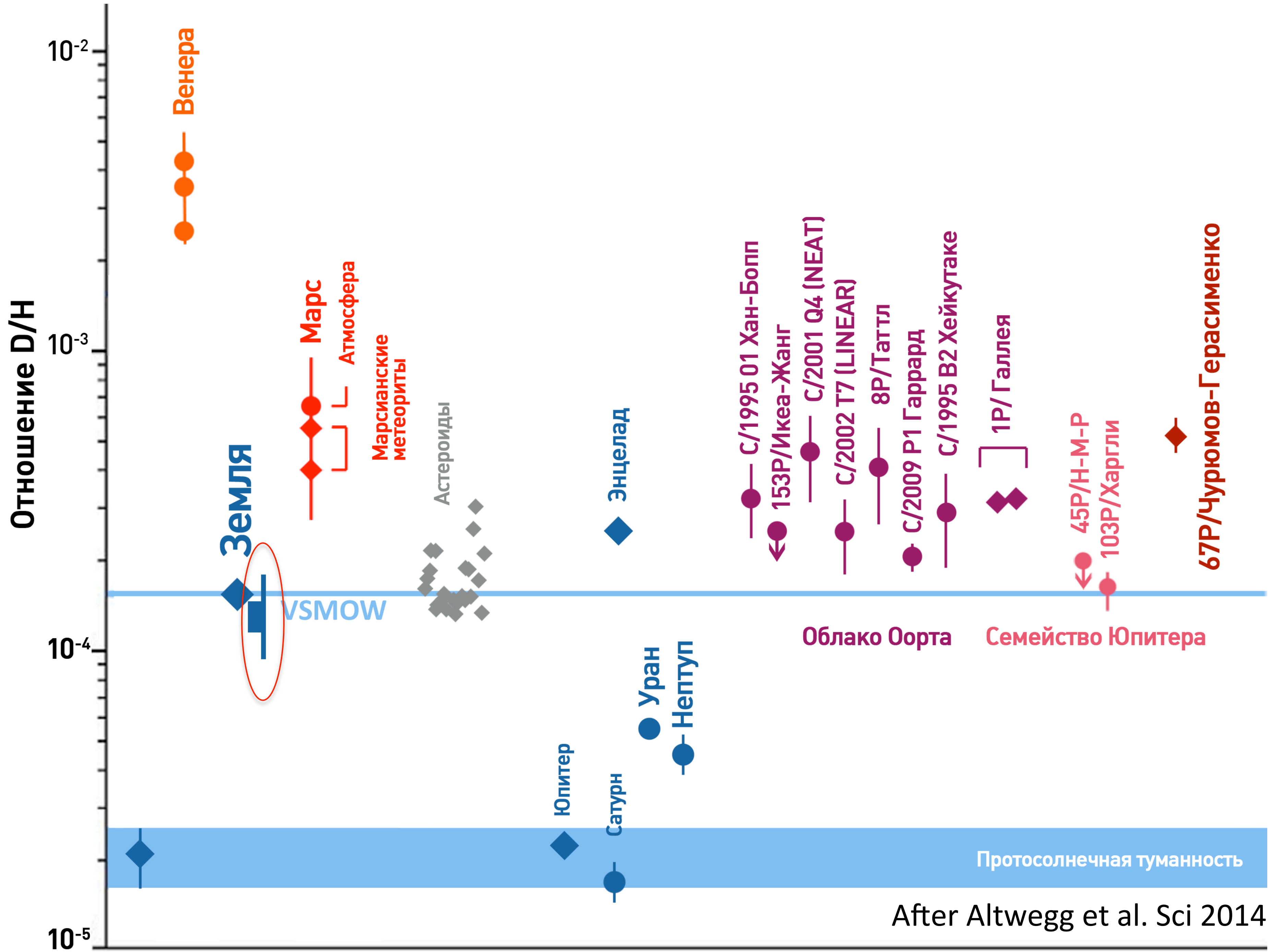
Noble gases

- The difference between the measured atmospheric abundances of non-radiogenic noble gases in Venus, Earth, and Mars is striking
- Many studies: Pepin 1991, 2006; Owen et al. 1992; Owen and Bar-Nun 1995; Dauphas 2003; Marty and Meibom 2007
- Earth might collided with 3-4 times more comets than Mars [Horner et al. 2009; Mousis et al. 2010] → ~3 times less noble gases at Mars (but not ~100 times less).
- Possible explanations:
  - Giant impacts on Earth and Mars (and not on Venus)
  - Hydrodynamic escape
  - Sequestration by CO_2 clathrates in the planet or in the solar nebula
- No satisfactory explanation so far



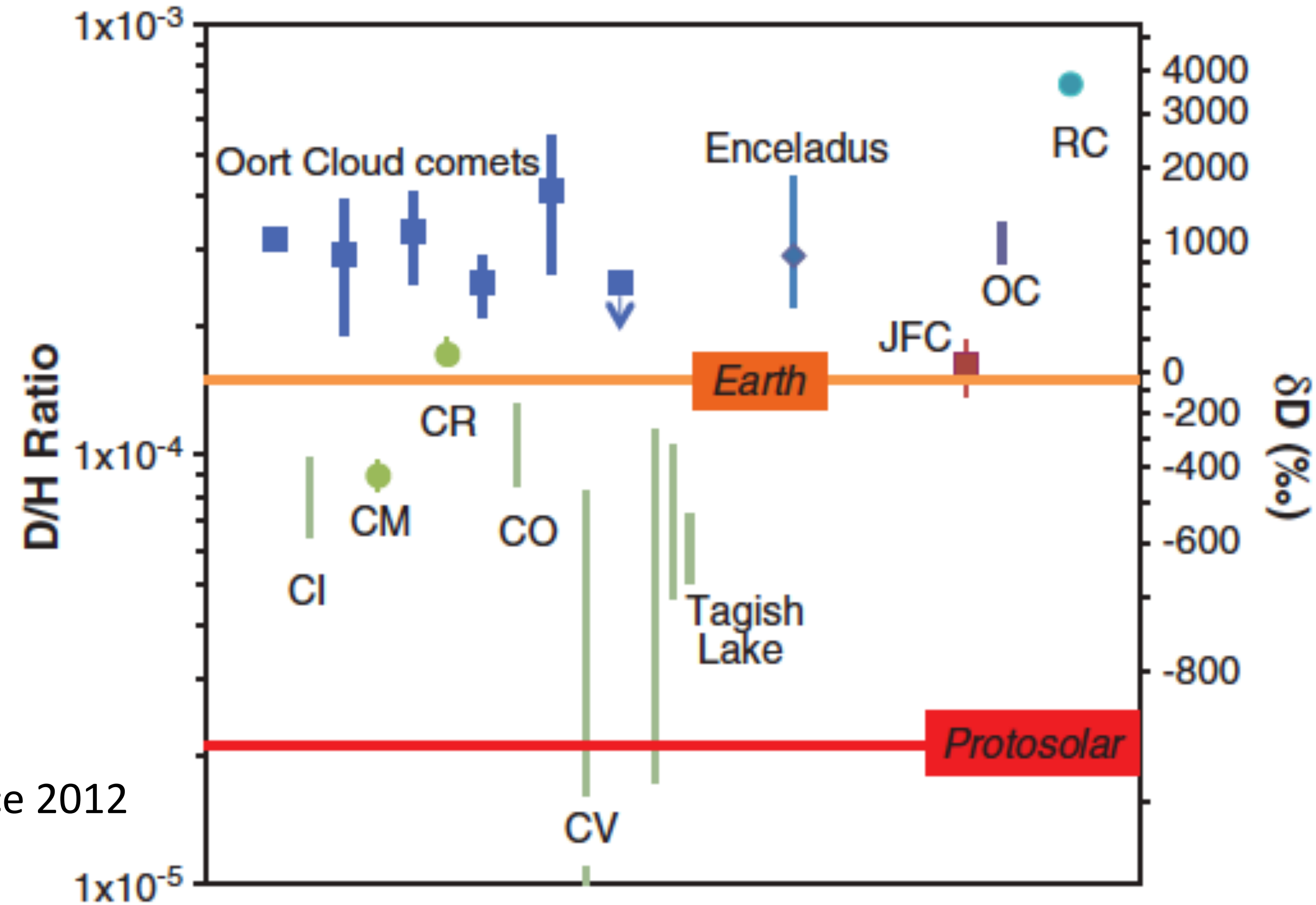






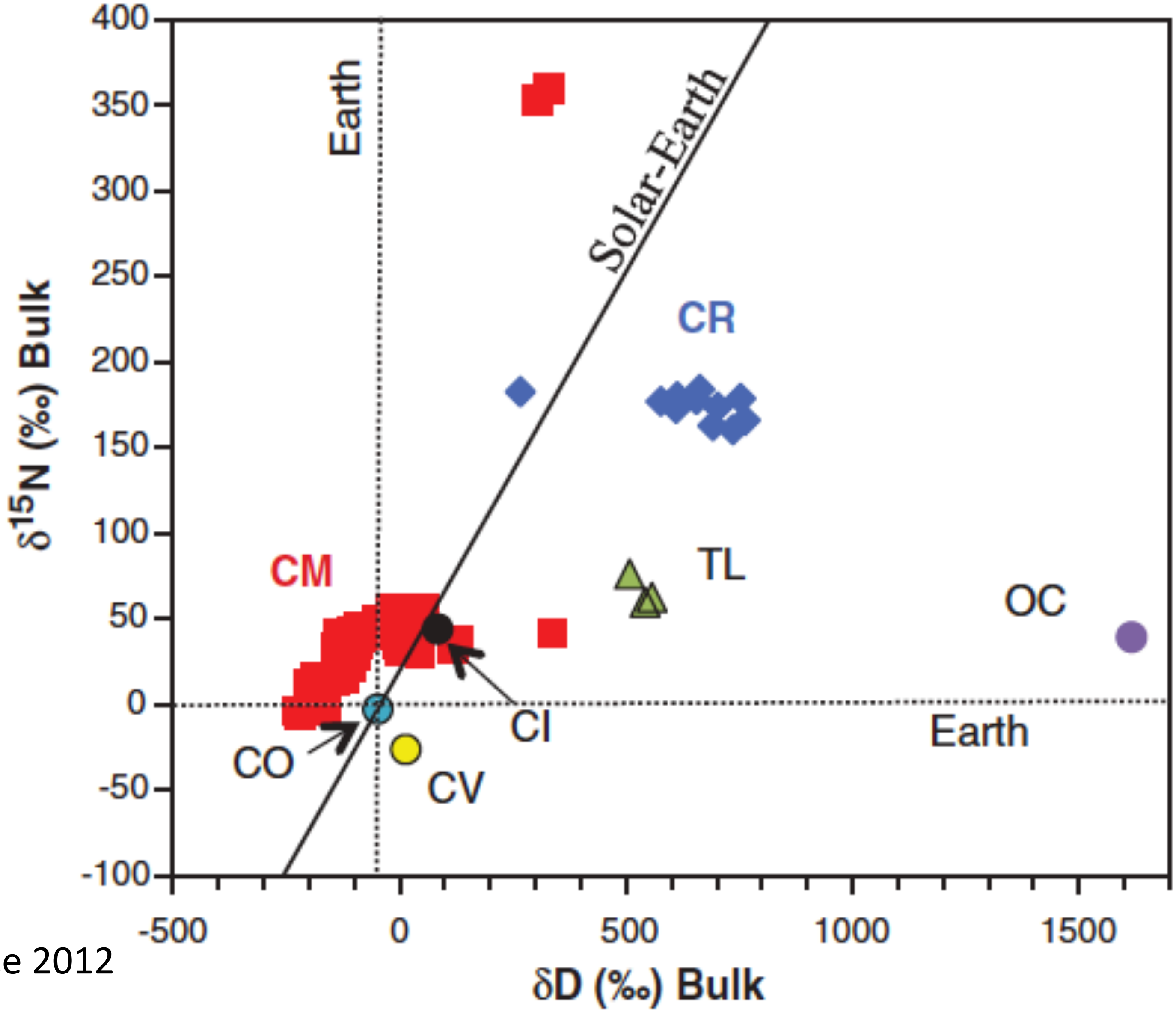
After Altwegg et al. Sci 2014

Fig. 2. Comparison of the estimated hydrogen isotopic compositions of water in various chondrite groups with those measured in Oort cloud and Jupiter family comets (JFC), and Saturn's icy moon Enceladus. See (3) for details and sources.



Alexander et al., Science 2012

Fig. 3. The bulk hydrogen and nitrogen isotopic compositions of chondrites (TL, Tagish Lake). The line connects the solar and terrestrial isotopic compositions. Bodies similar to chondrites are potential sources of Earth's volatiles. For reasons discussed in the text, CI-like material with ~10% contributions of material with isotopically solar compositions, but a roughly chondritic H/N value, can most simply explain Earth's bulk hydrogen and nitrogen isotopic compositions (*3*).

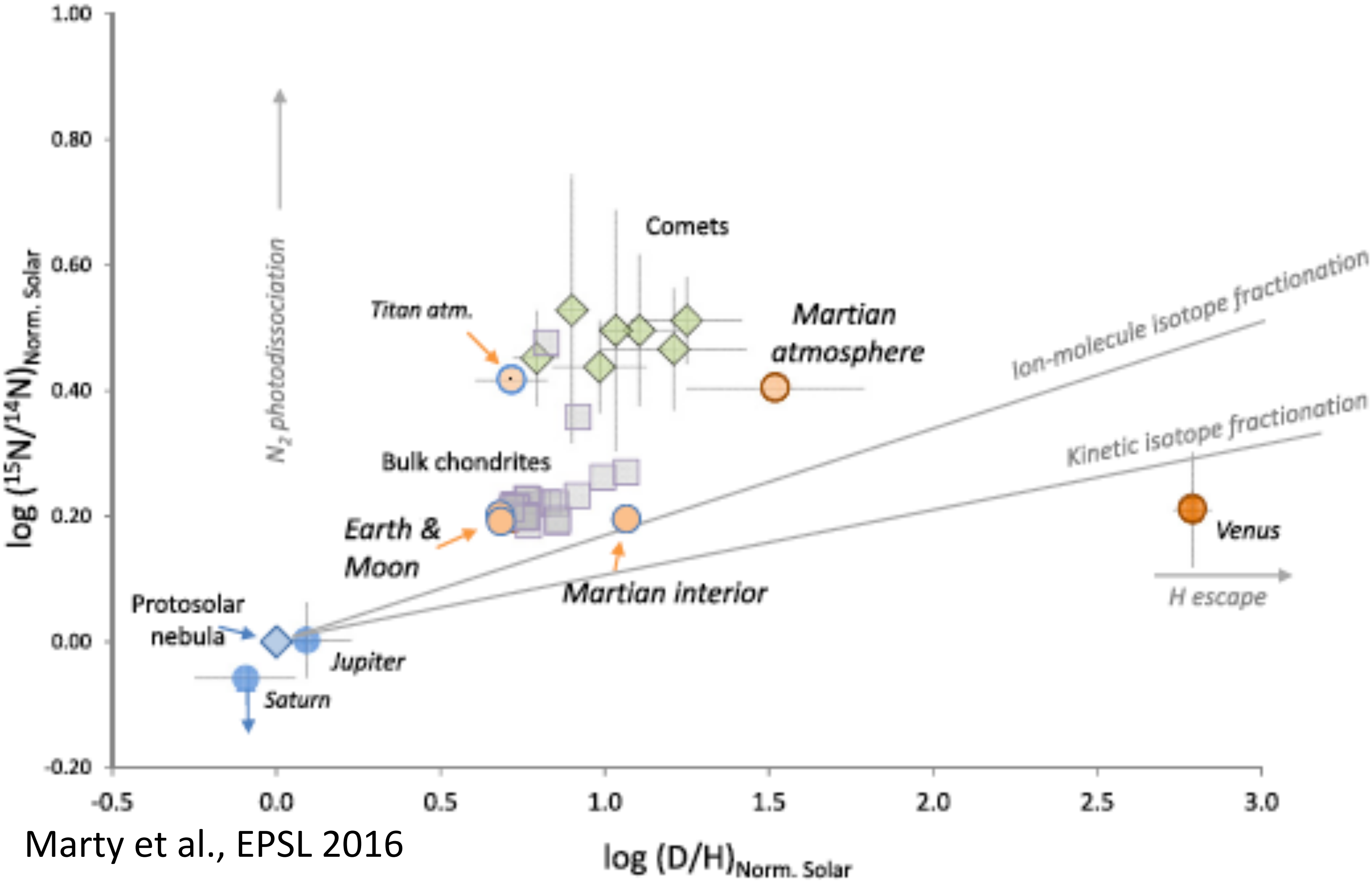


Alexander et al., Science 2012

Earth volatiles: CI-type +10% of primordial nebula composition

Rosetta model of cometary composition

- contribution of cometary volatiles < few % of the total volatile inventory of the Earth.
- The isotope signatures of H, N, Ne and Ar can be explained by mixing between two endmembers, solar and chondritic, and do not require isotopic fractionation during hydrodynamic escape



Marty et al., EPSL 2016

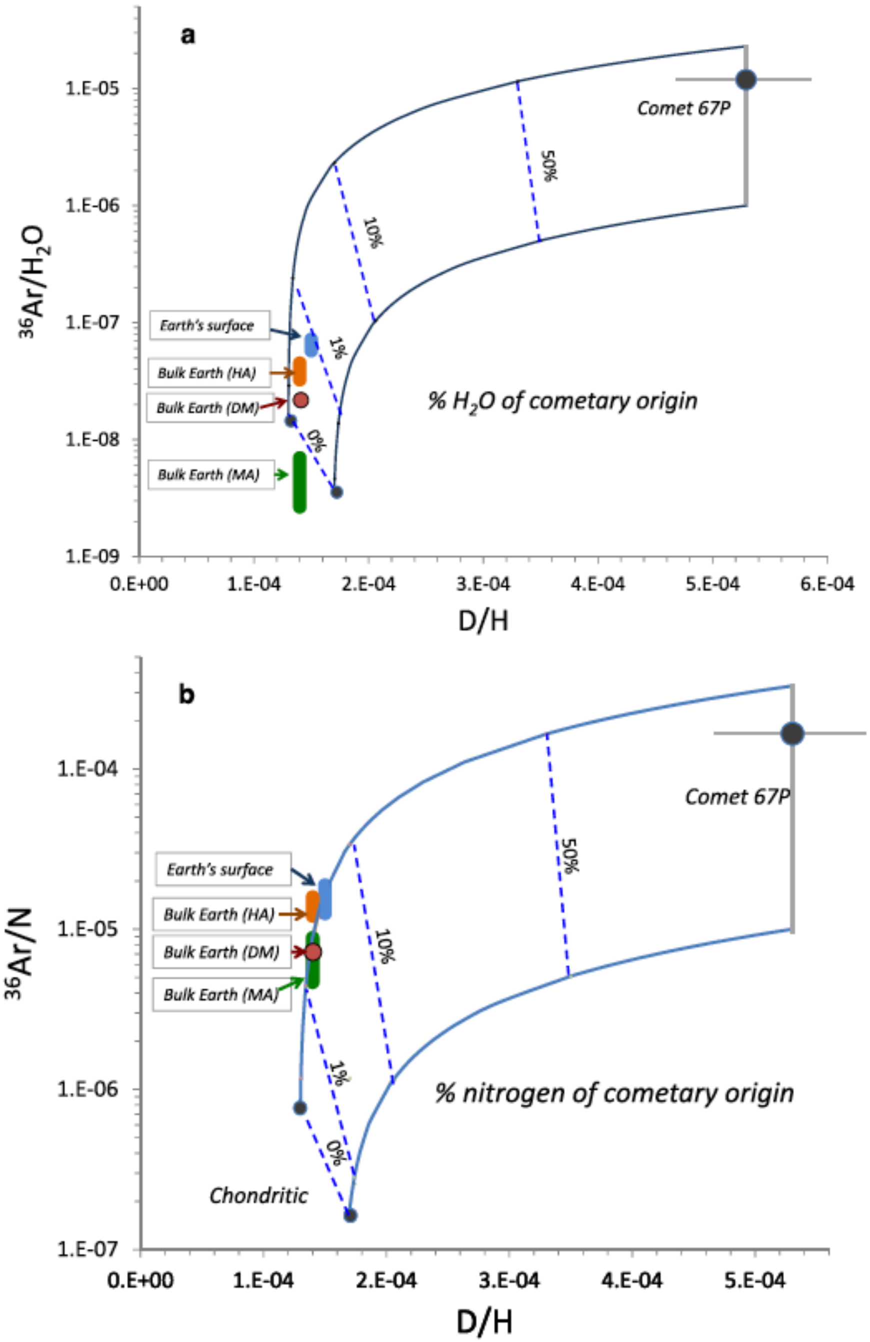


Fig. 3. $^{36}Ar/H_2O$ (a) and $^{36}Ar/N$ (b) versus D/H mixing diagrams between cometary and chondritic (asteroidal) end-members. The mixing curves are constructed as

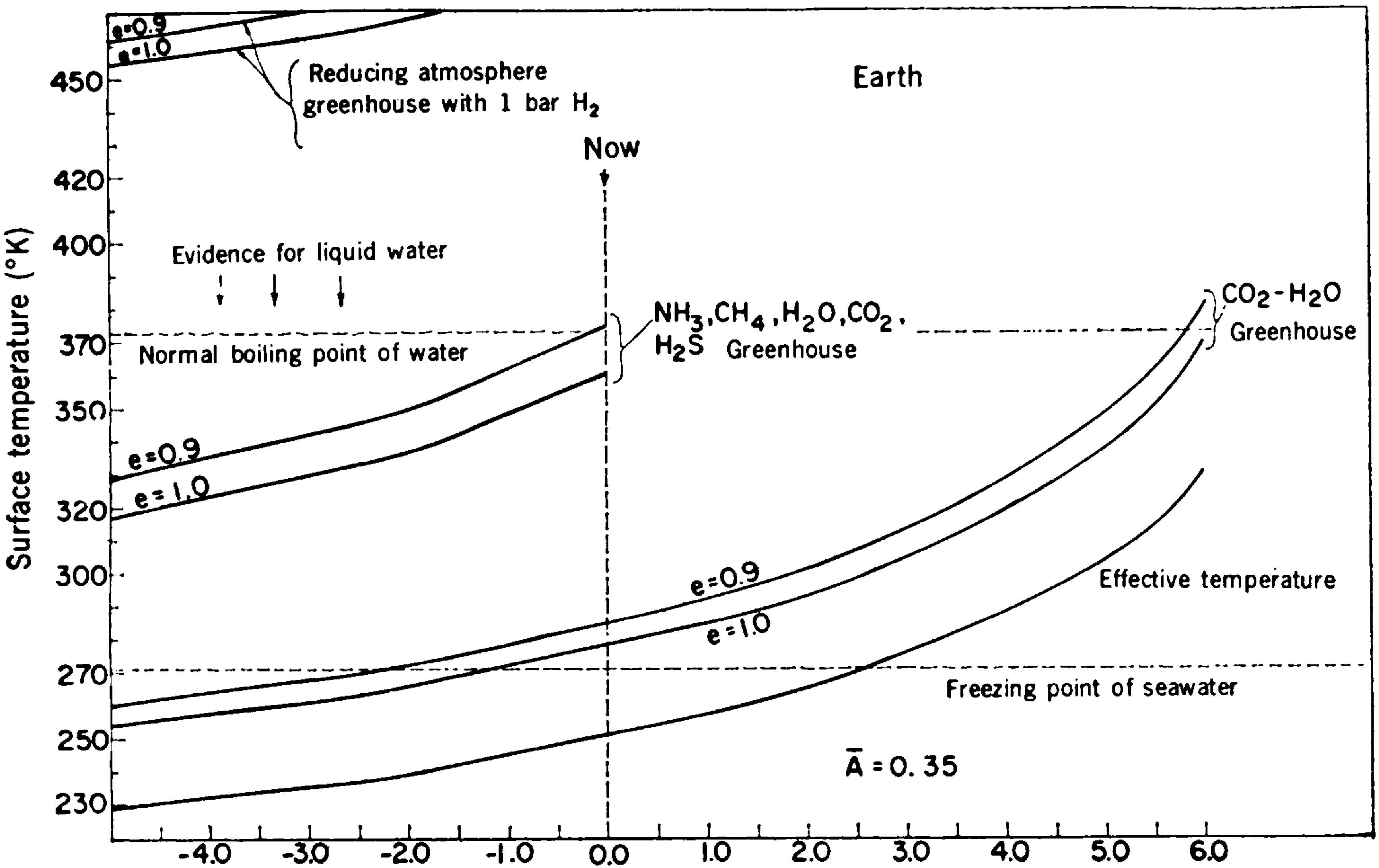
- minor contribution of cometary volatiles to the Earth's inventory for water (≤1%), carbon (≤1%), and nitrogen species (a few % at most).
- cometary contributions may be significant for the noble gases
- may be acquired during LHB

- observations are consistent with volatiles of Earth and Mars being trapped initially from the nebular gas and local accreting material, then progressively added to by contributions from wet bodies from increasing heliocentric distances.

- concurs with ^{40}Ar data

Marty et al., EPSL 2016

Faint young Sun paradox

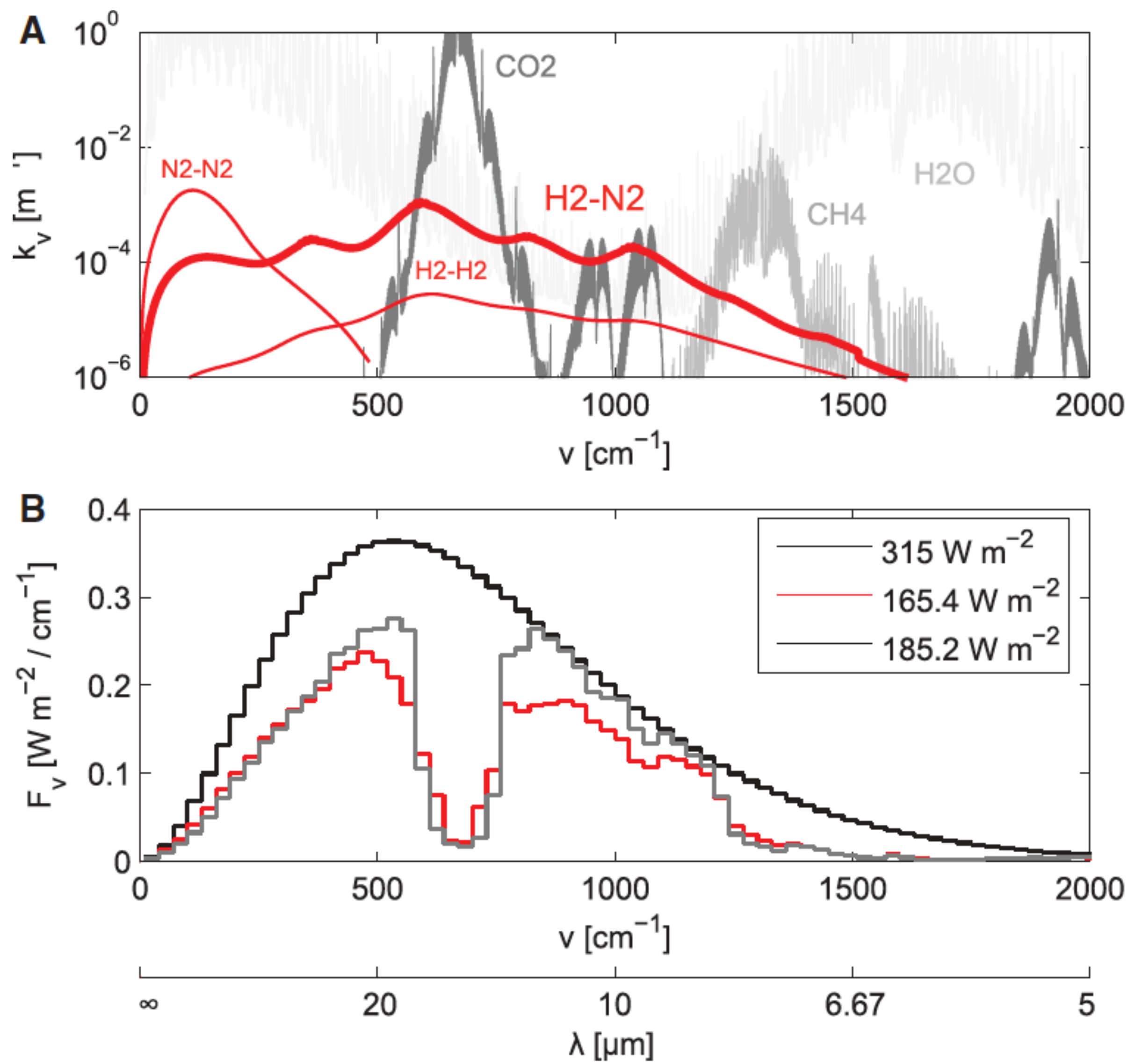


Sagan& Mullen 1972

Hydrogen-Nitrogen Greenhouse Warming in Earth's Early Atmosphere

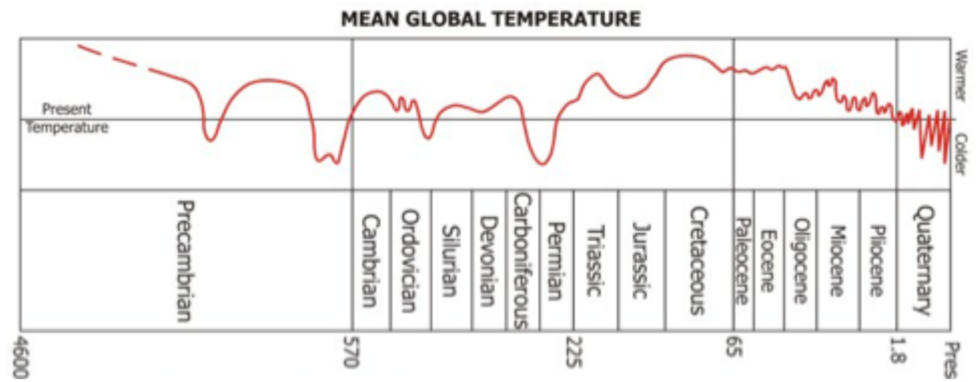
Science 2013

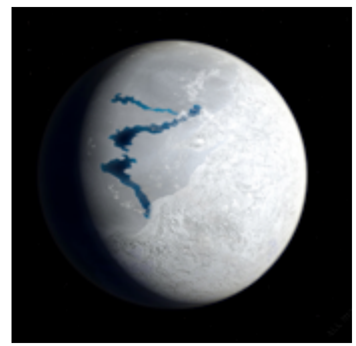
Robin Wordsworth* and Raymond Pierrehumbert

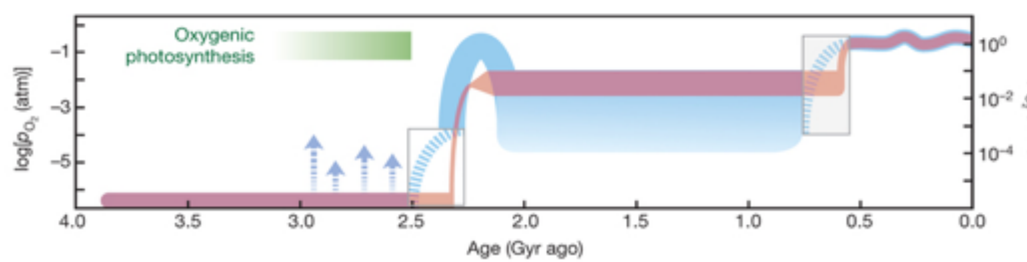


Atmosphere of Earth as a terrestrial planet

- Ocean (GEL= 2.8 km)
- CO_2 sequestration
- Albedo effect
  - Very low albedo of water surface (0.04) → effective heating
  - High albedo of clouds regulates the warming (negative feedback)
  - Even higher albedo of ice and snow amplifies cooling (positive feedback)
- Snowball Earth: Total glaciations (3-4 episodes, 250, 650-750 mln y; **2.4-2.1 Ga**)
  - To interrupt these deepest ice ages required 0.13-0.2 bars of CO_2 [Pierrehumbert et al 2004, 2011]
- 100-300 ppm of CH_4 ?[Pavlov et al. Geol 2013]
- Rise of oxygen; forming ozone layer







[Lyons et al. Nature 2014]

LETTERS
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Earth's air pressure 2.7 billion years ago constrained to less than half of modern levels

Sanjoy M. Som[1*†], Roger Buick[1], James W. Hagadorn[2], Tim S. Blake[3], John M. Perreault[1†], Jelte P. Harnmeijer[1†] and David C. Catling[1]

Climate evolution: Evidence from volatiles

- Similar initial volatile inventory of the terrestrial planets
- Very simple backward extrapolation of volatiles (after Krasnopolsky, PSS 2011)

Initial (now)	CO_2, bar	N_2, bar	H_2O, km
Venus	**90** (90)	**2** (2)	**2.3** (1.3 cm)
Earth	**112** (5×10^{-4})	2.5 (0.8)	**2.8** (2.8)
Mars	**16** (6 mbar)	0.35 (0.1 mbar)	**1.4** (30 m)

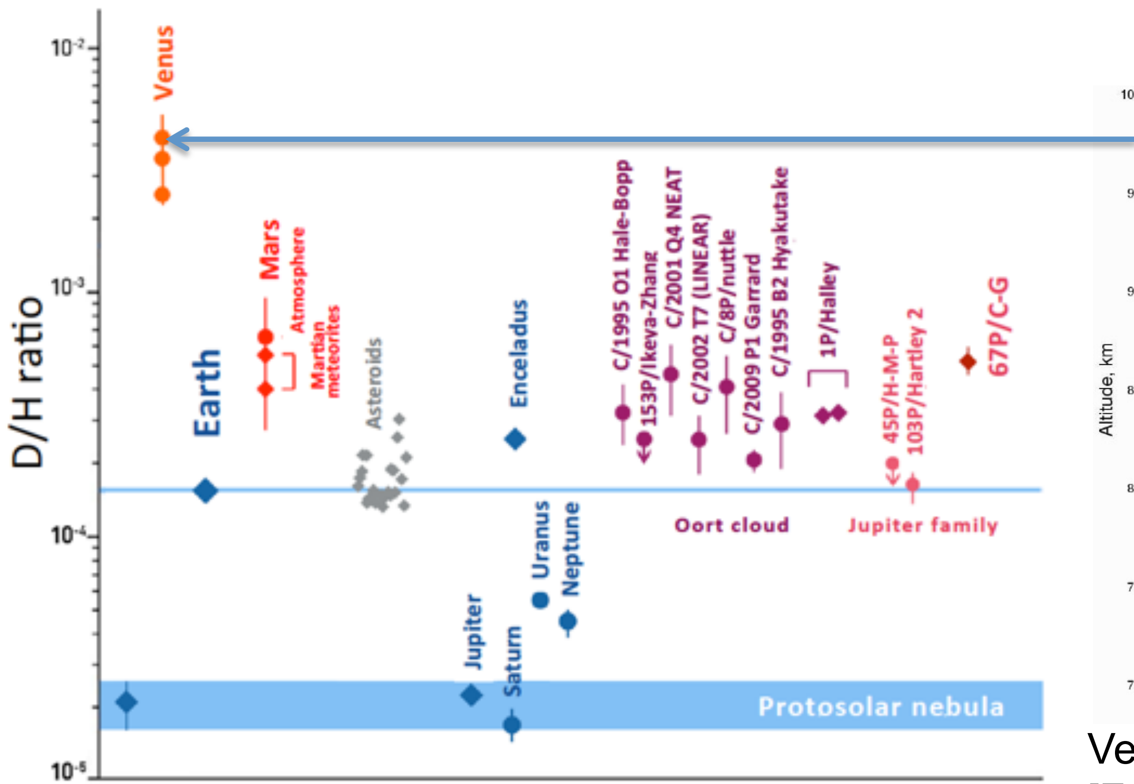
$$P_i = P_0\left(\frac{g_i}{g_0}\right)^2$$

0.6–2.7 cosmogonic
Lunine et al., Icarus 2003

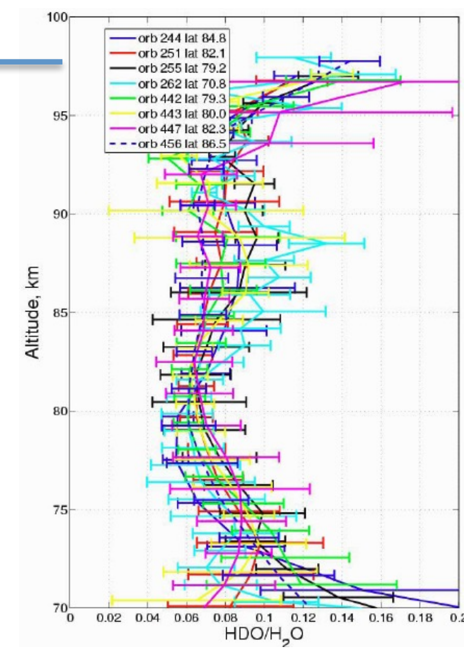
Preferential escape from Mars and Venus

- Initial GEL inferred from D/H ratios: Mars -150 m; Venus -2 m

➔ Hydrodynamic escape

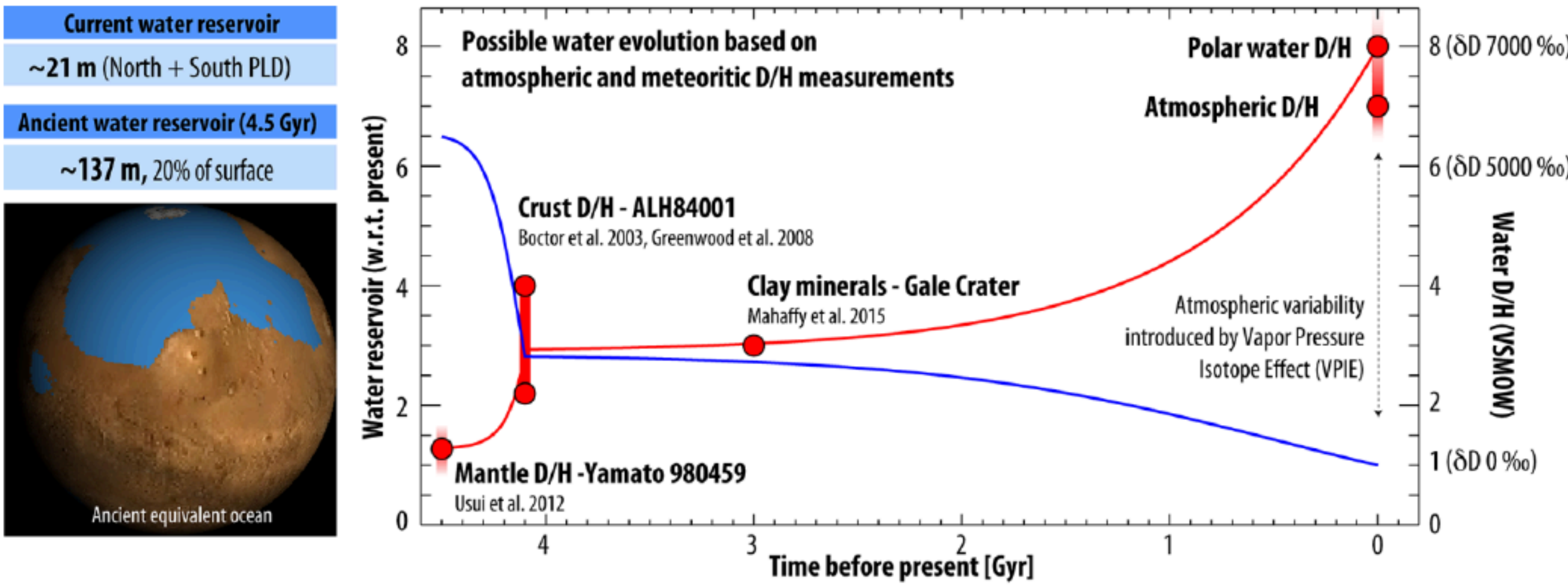


After Altwegg et al. Sci 2014



Venus Express: D/H=240Terr
[Fedorova et al., 2008]

Mars water reservoirs estimates based on D/H



Villanueva et al. Sci 2015

See also Krasnopolsky, Icarus 2015

Isotopes of noble gases

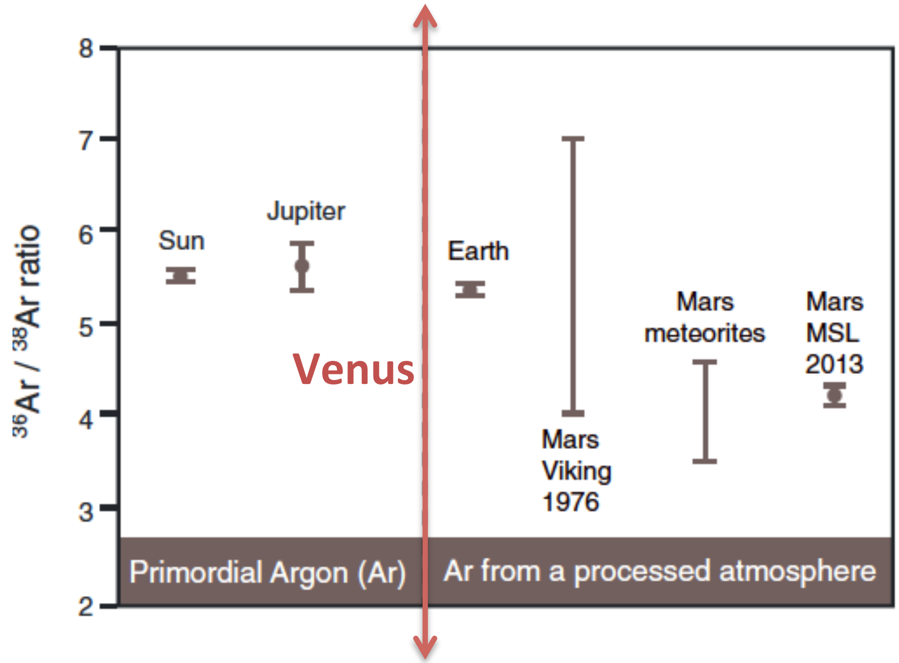
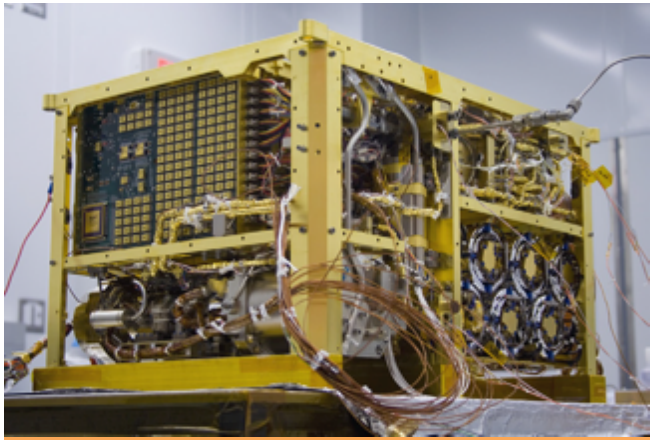


Fig from Atreya et al. GRL 2013; Mahaffy et al. Sci 2013

For D/H etc. isotopes see Webster et al 2013

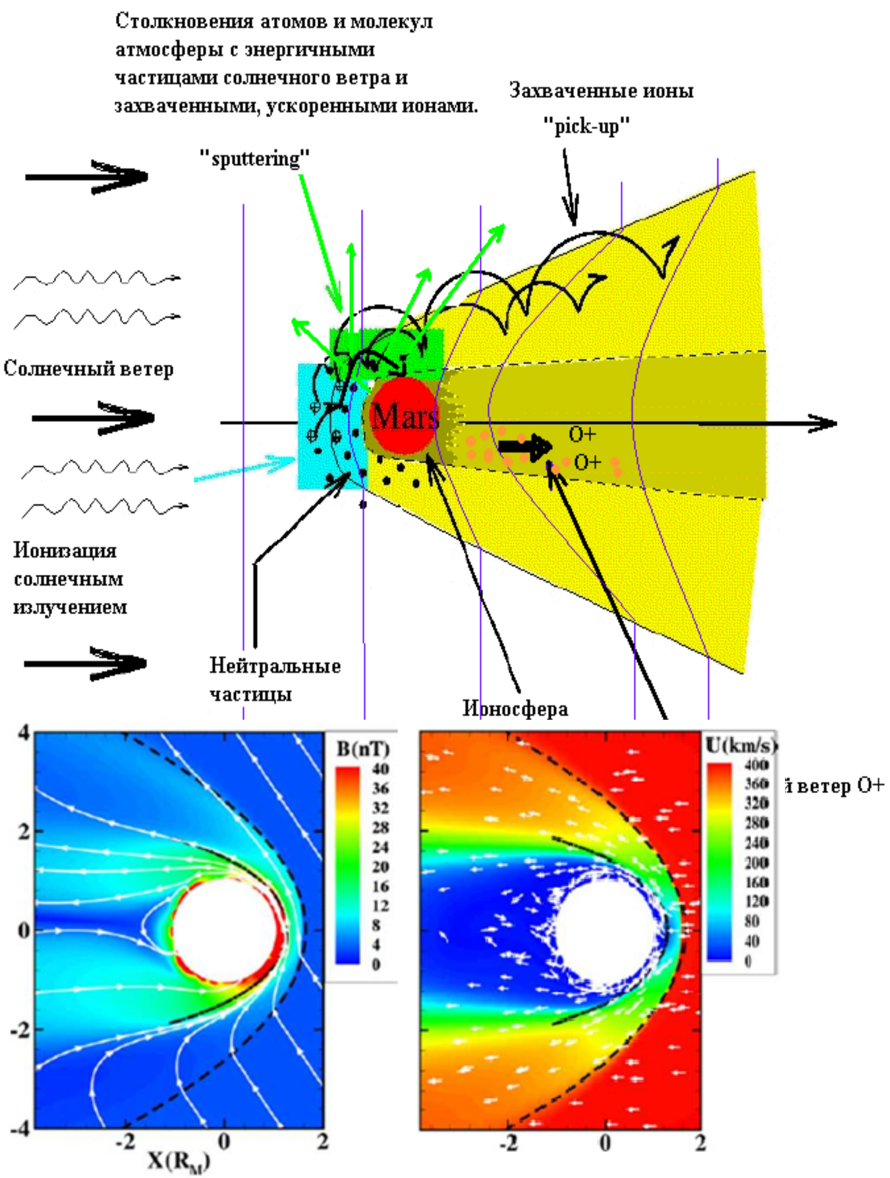
- Proves that Mars meteorites are indeed from Mars
- significant loss of argon of 50% up to 85–95% in the past 4 billion years
- confirms substantial preferential escape

New instruments (ex. MSL CGMS with enrichment) allow to increase drastically the accuracy of measurements



- SAM=Sample Analysis at Mars suite @ MSL
- Pyrolysis (59)
- Wet extraction (9)
- Gas chromatograph
- Tuneable Laser spectrometer
- Quadruple Mass-Spectrometer

СОЛНЕЧНЫЙ ВЕТЕР «СДИРАЕТ» АТМОСФЕРУ МАРСА

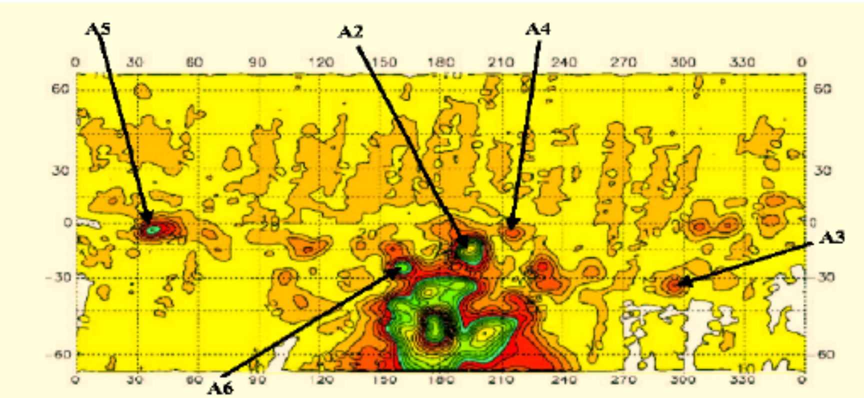


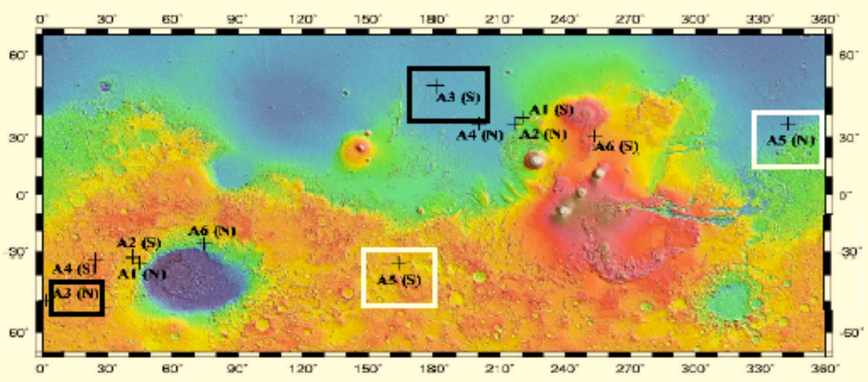
Основные механизмы:

- **“pick-up”** захват ионизованных планетарных ионов потоком солнечного ветра
- **“sputtering”** столкновения атомов и молекул атмосферы с ускоренными ионами солнечного ветра и захваченными (“pick-up”) планетарными ионами.
- **планетарный ветер**: захват ионов магнитным полем солнечного ветра, проникающим в ионосферу.

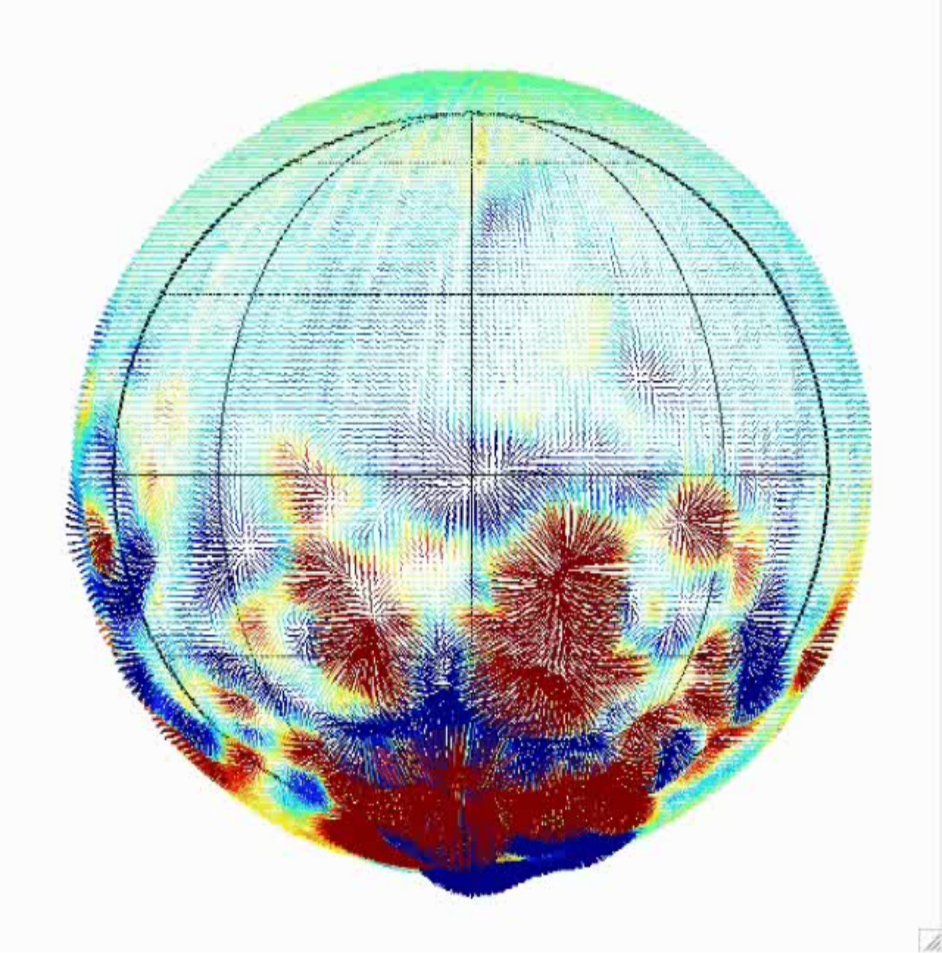
Марс: Что произошло с планетарным динамо?

Магнитные аномалии на поверхности Марса





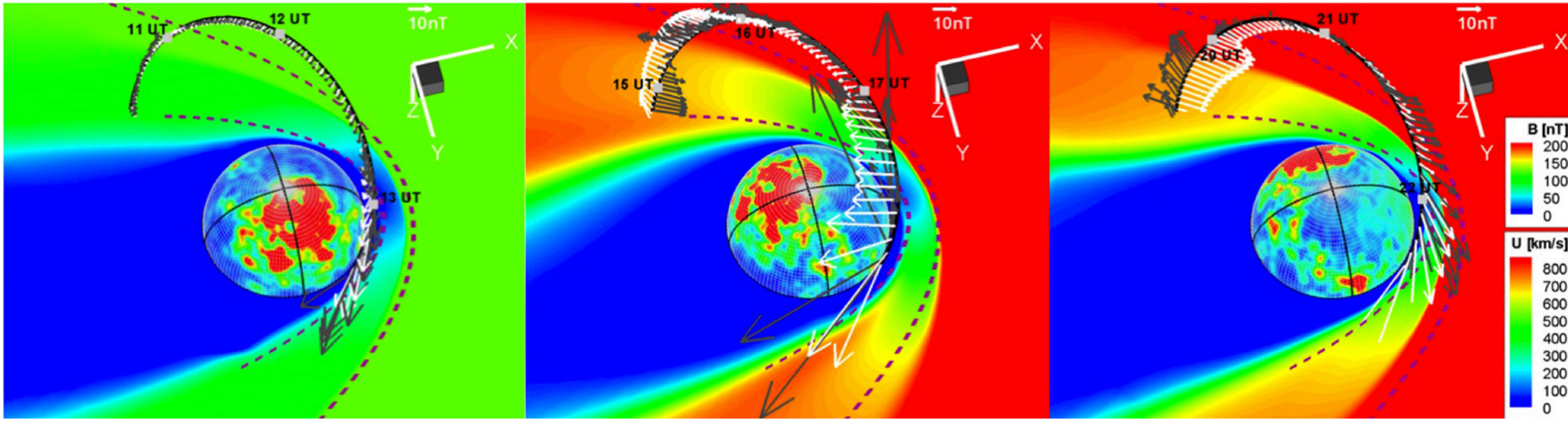
Положение полюсов древнего магнитного поля Марса на поверхности



- **Активное динамо существовало 4 млрд. лет назад. Причина затухания – остывание планеты.**
- **Другая гипотеза – магнитное поле Марса находится в процессе переориентации?**

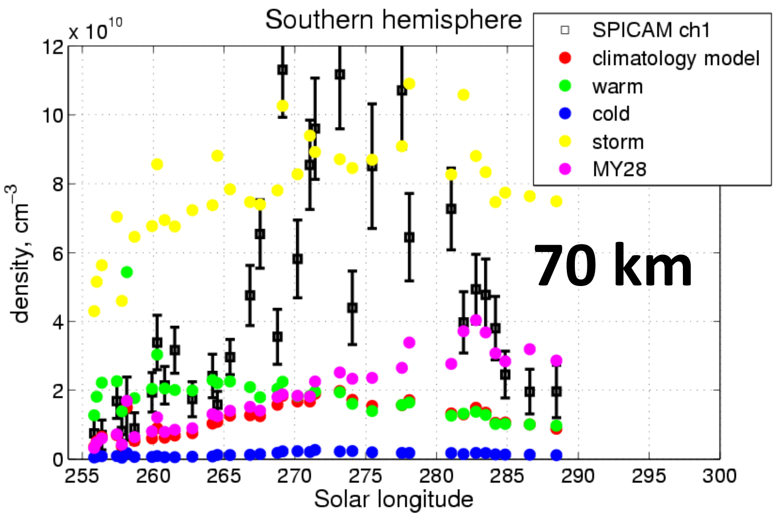
Preferential escape from Mars

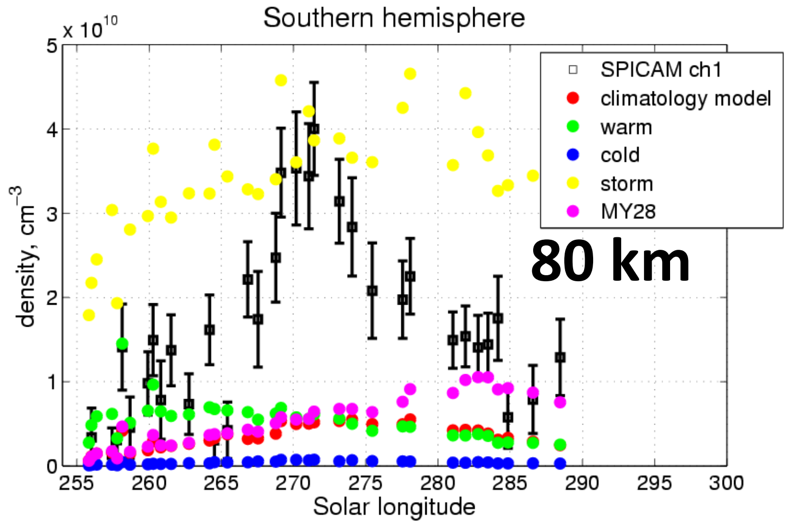
- Contemporary (thermal and non-thermal mechanisms) can remove from Mars 3-80 GEL of water (Fobos-2; Mars Express) [Barabash et al. Sci 2007; see Vaisberg PSS 2015 for review of earlier estimates]
- New MAVEN results: During observed interplanetary coronal mass ejection (ICME) escape rate for O_2^+ enhanced by a factor of 20 [Jakosky et. Science 2015; Hara et al., GRL 2016]
- Given the likely prevalence of ICME-like conditions earlier in solar-system history it is possible that ion escape rates at that time were dominated by storm events



More news on the escape from Mars

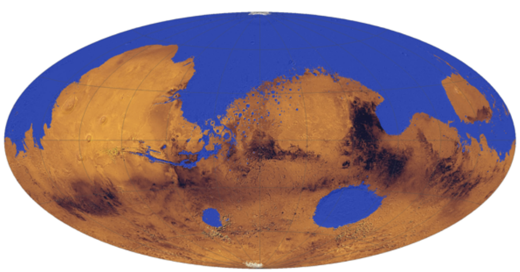
- Variability of hydrogen corona from HST observations [Clarke et al. 2014] and from SPICAM/Mars Express data [Chaffin et al. 2014]
- Strong seasonal dependence [Bhattacharyya et al. 2015]
- Dependence on H_2O vertical profile and the dust storm [Fedorova et al., in prep]

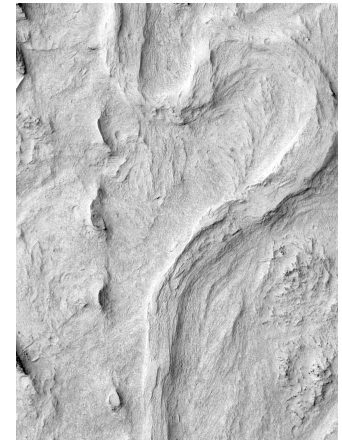


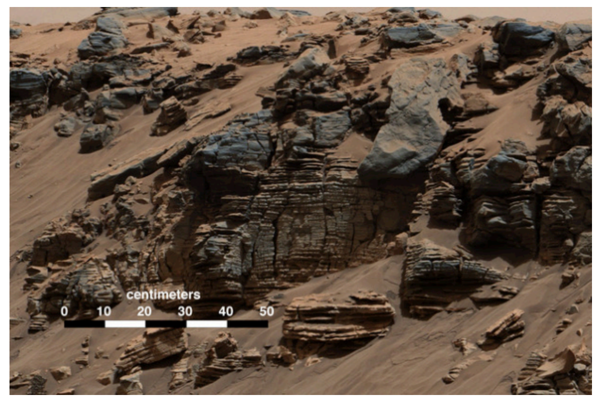


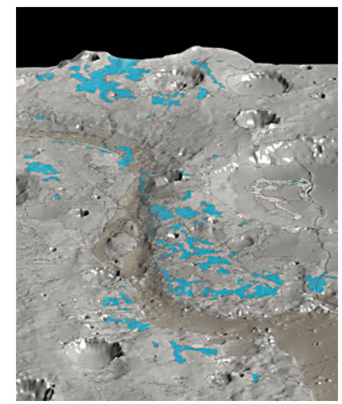
РАННИЙ ТЕПЛЫЙ МАРС

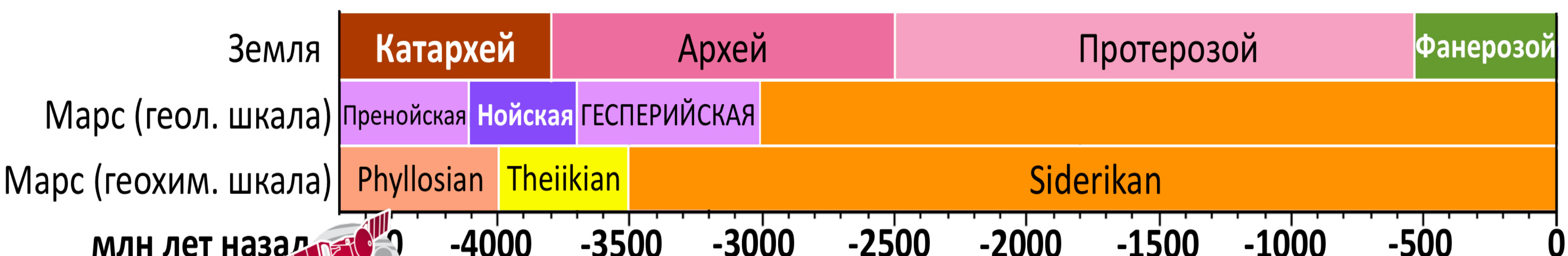
- Следы обильной жидкой воды на поверхности
  - 3.5 млрд. лет
  - ~500 м воды
- Минералы формировались в присутствие воды
  - Глины
  - Карбонаты









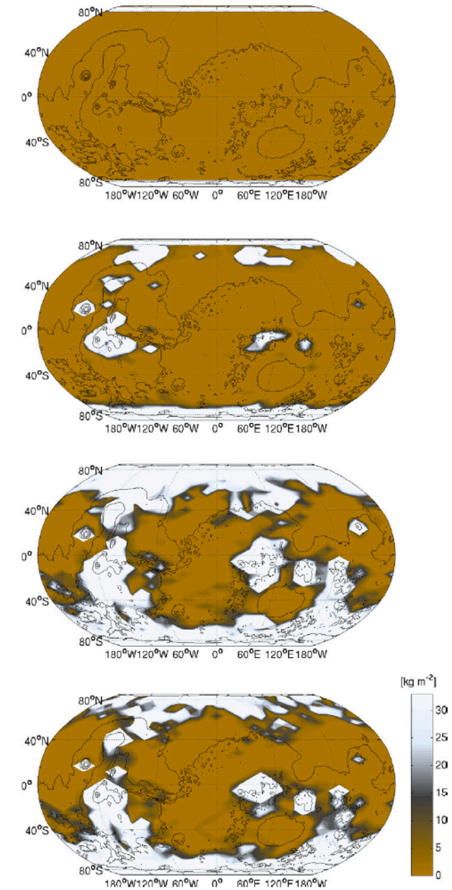


mars express

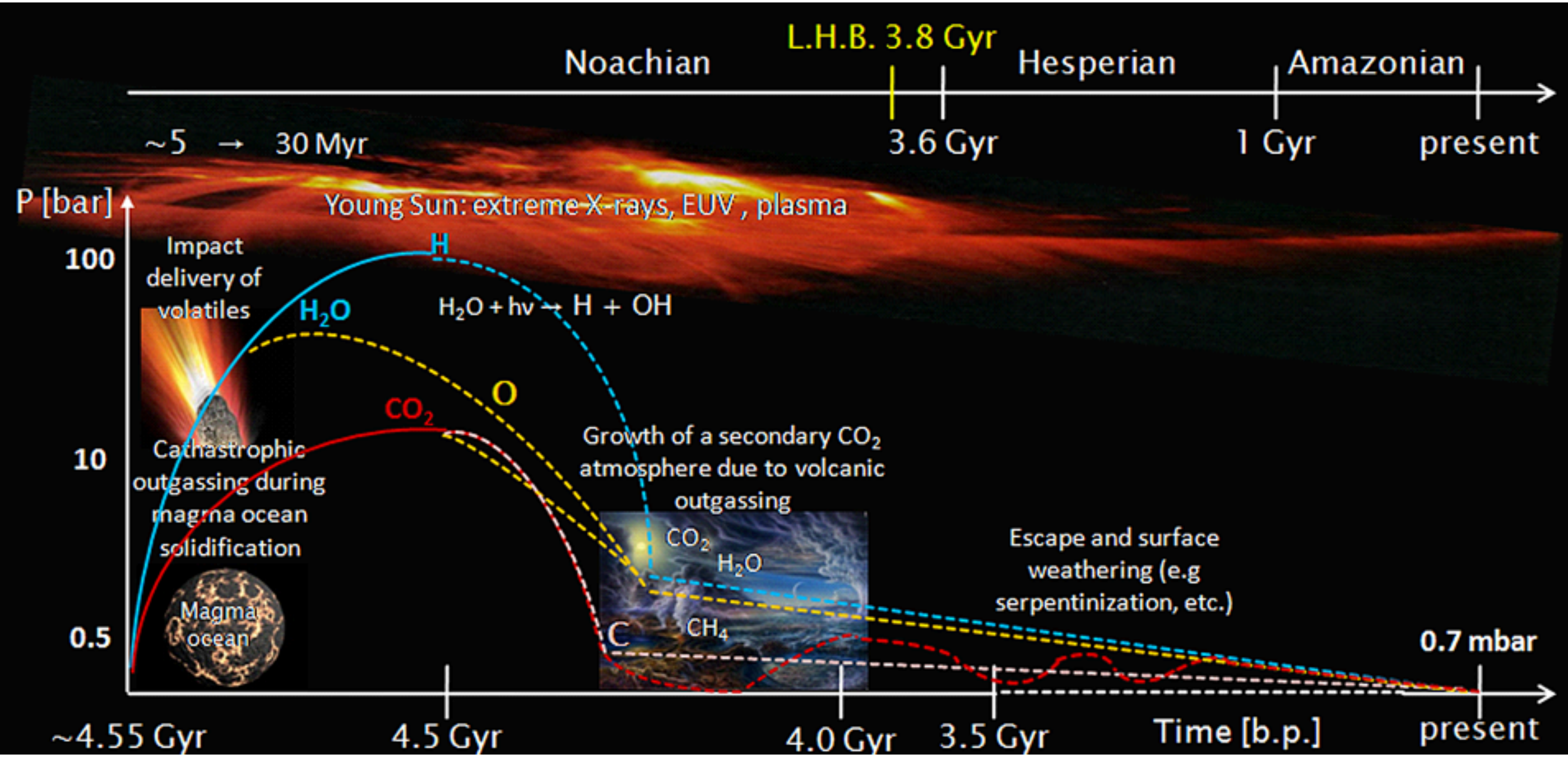
OMEGA/Mars Express [Bibring et al., 2005]

Ранний холодный Марс

- Fairen et al. NatGeo 2011. Cold glacial oceans would have inhibited phyllosilicate sedimentation on early Mars.
- Forget, F. et al. Icarus 2013. 3D modelling of the early Martian climate under a denser CO_2 atmosphere: temperatures and CO_2 ice clouds.
- Wordsworth, R. et al. Icarus 2013. Global modelling of the early Martian climate under a denser CO_2 atmosphere: water cycle and ice evolution.
- Ramirez et al. NGeo 2013. Warming early Mars with CO_2 and H_2
- Batalha et al. Icarus 2015 Testing the early Mars H_2–CO_2 greenhouse hypothesis with a 1-D photochemical model
- Wordsworth, R. D. et al. JGRE 2015. Comparison of “warm and wet” and “cold and icy” scenarios for early Mars in a 3D climate model.
- Ramirez & Kasting, Icarus 2017. Could cirrus clouds have warmed early Mars?



Эволюция атмосферы Марса



Lammer et al. SSRv 2013

The case for Venus

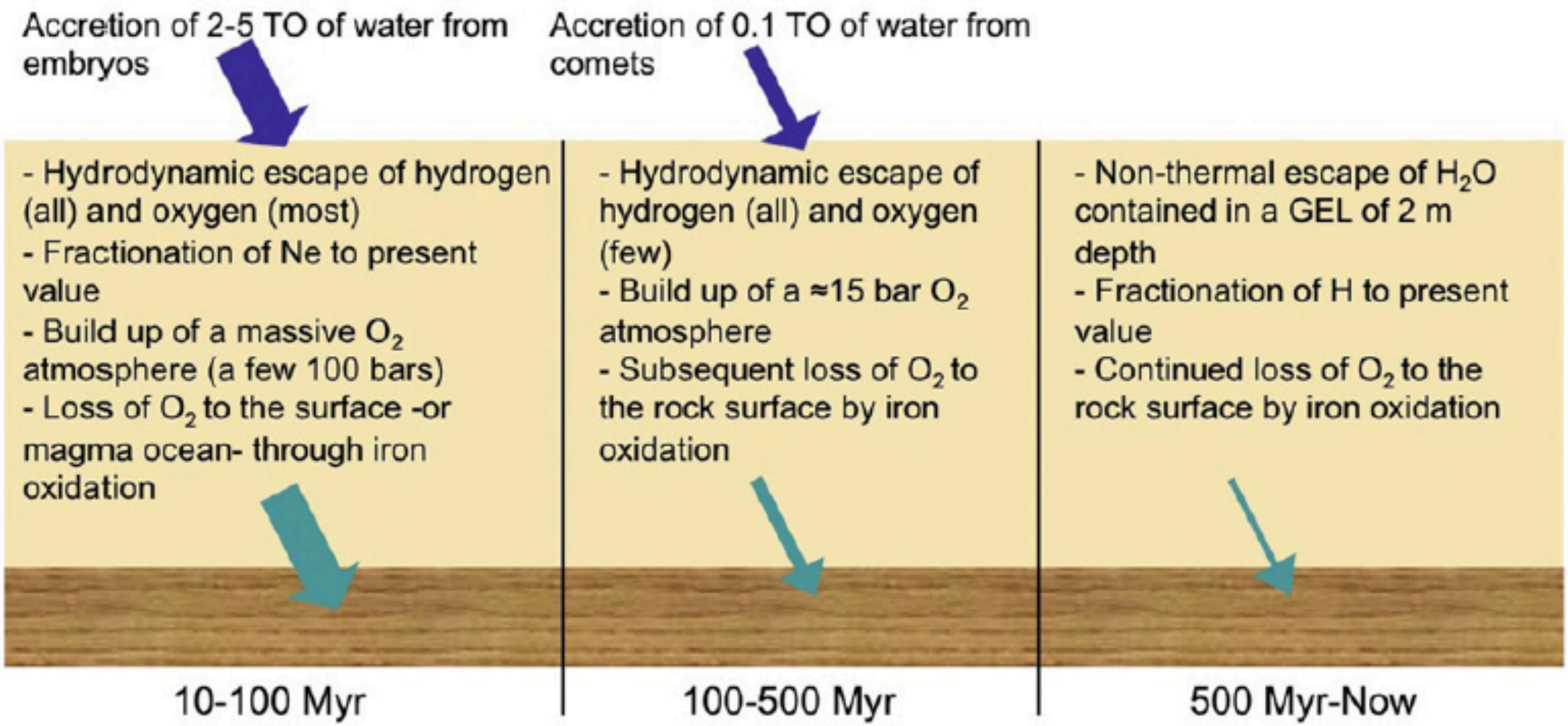
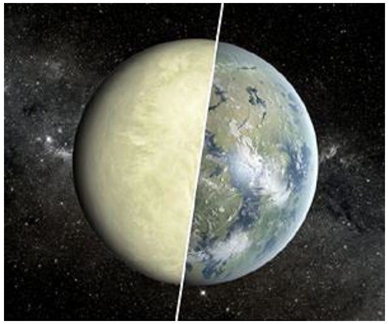
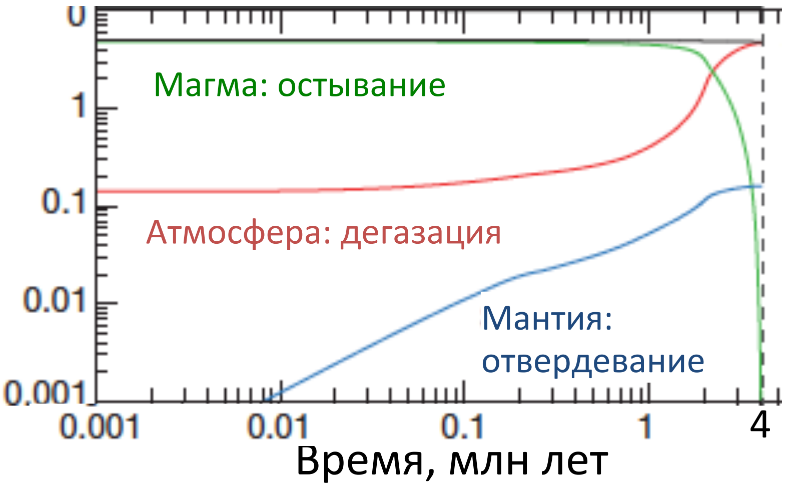


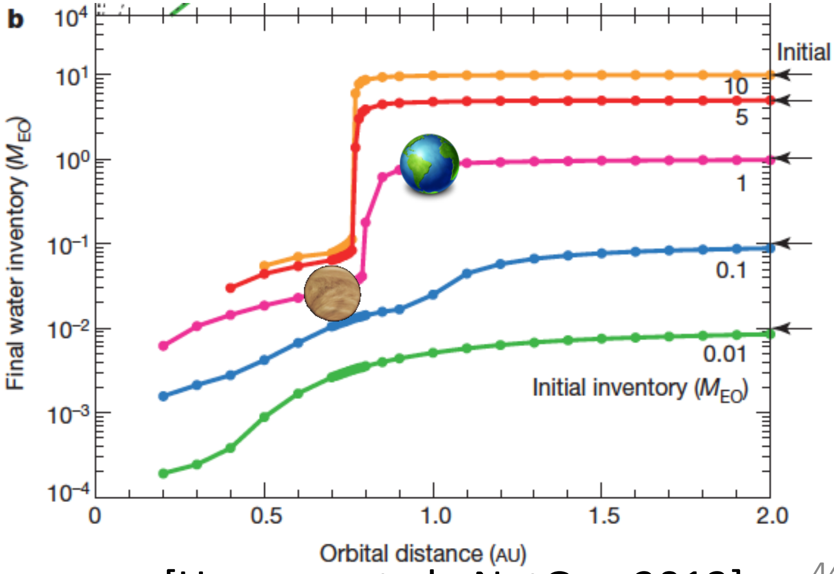
Fig. 2. Possible scenario of water history on Venus (from Gillmann et al., 2009).

Почему Венера так отличается от Земли?





- Ранняя эволюция: первые 4 млн лет
- Остывание океана магмы, дегазация
- Паровая атмосфера поглощает излучение планеты (исходящее излучение <300 Вт/м^2)
- Планета не остынет, пока не уйдет вода (гидродинамический вынос)
- Критическое расстояние до звезды: в случае Солнца 0.7 а.е.



[Hamano et al., NatGeo 2013]

Geophysical Research Letters

RESEARCH LETTER
10.1002/2016GL069790

Was Venus the first habitable world of our solar system?

M. J. Way[1,2], Anthony D. Del Genio[1], Nancy Y. Kiang[1], Linda E. Sohl[1,3], David H. Grinspoon[4], Igor Aleinov[1,3], Maxwell Kelley[1], and Thomas Clune[5]

Key Points:

- Venus may have had a climate with liquid water on its surface for editorial

Nature Geoscience July 2016

Earth's changeable atmosphere

Billions of years ago, high atmospheric greenhouse gas concentrations were vital to life's tenuous foothold on Earth. Despite new constraints, the composition and evolution of Earth's early atmosphere remains hazy.

Missions and measurements needed

- Venus:
  - Venus Express is not yet fully digested
  - High expectations from Akatsuki
  - Need for *in situ* mission (ex. Venera-D). Modern instruments can do a lot!
  - Need for SAR mission (volcanism, ex. VERITAS)
  - Need for better escape characterization
- Mars:
  - MAVEN, MOM, ExoMars TGO, UAE Mars Orbiter are atmospheric missions. But something could be improved already now
  - Better meteorological coverage (Vikings … MSL)

СПАСИБО ЗА ВНИМАНИЕ