Comparative Atmospheric Evolution

Robin Wordsworth

July 15, 2019

Sagan Workshop, Pasadena

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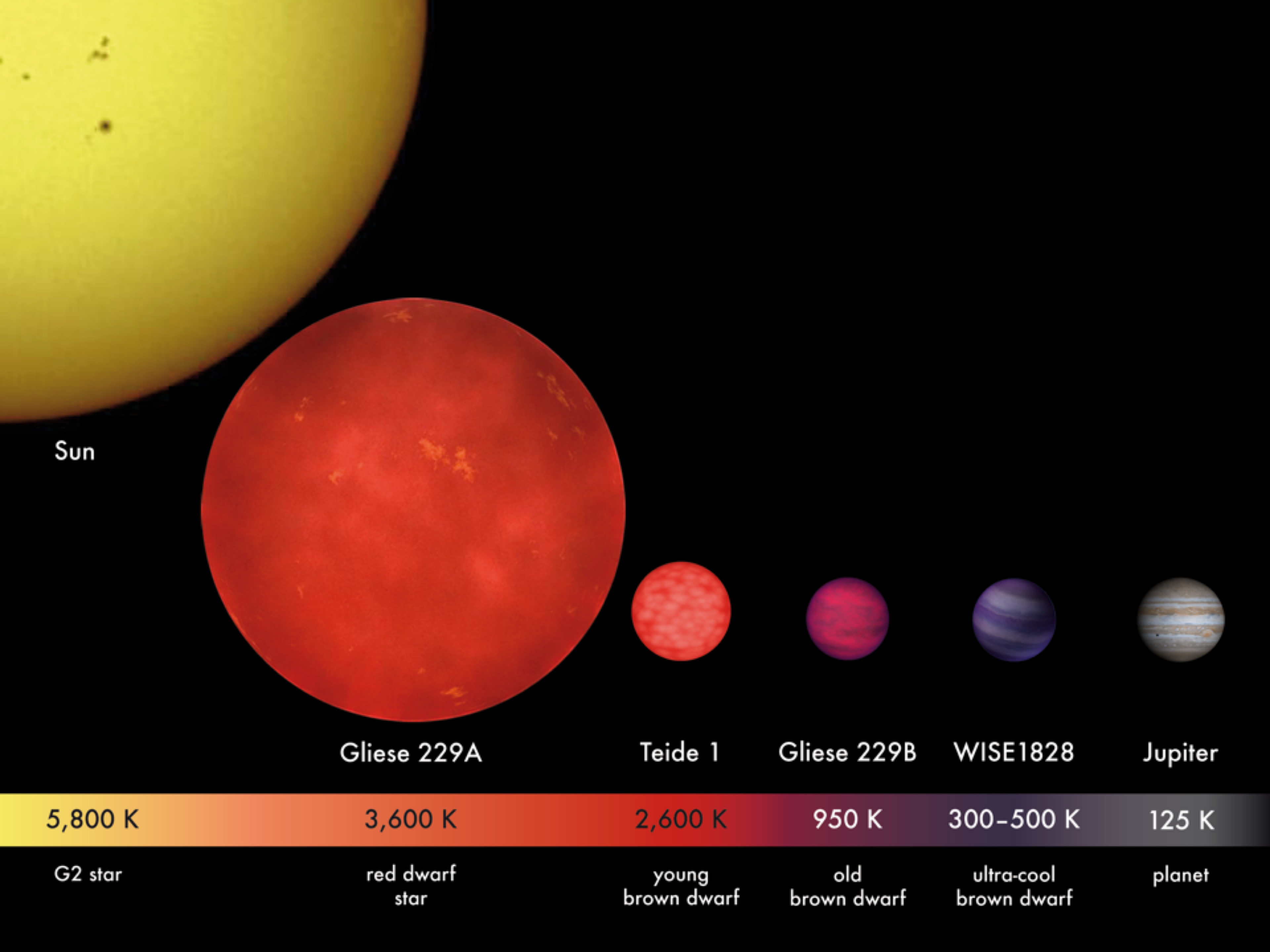
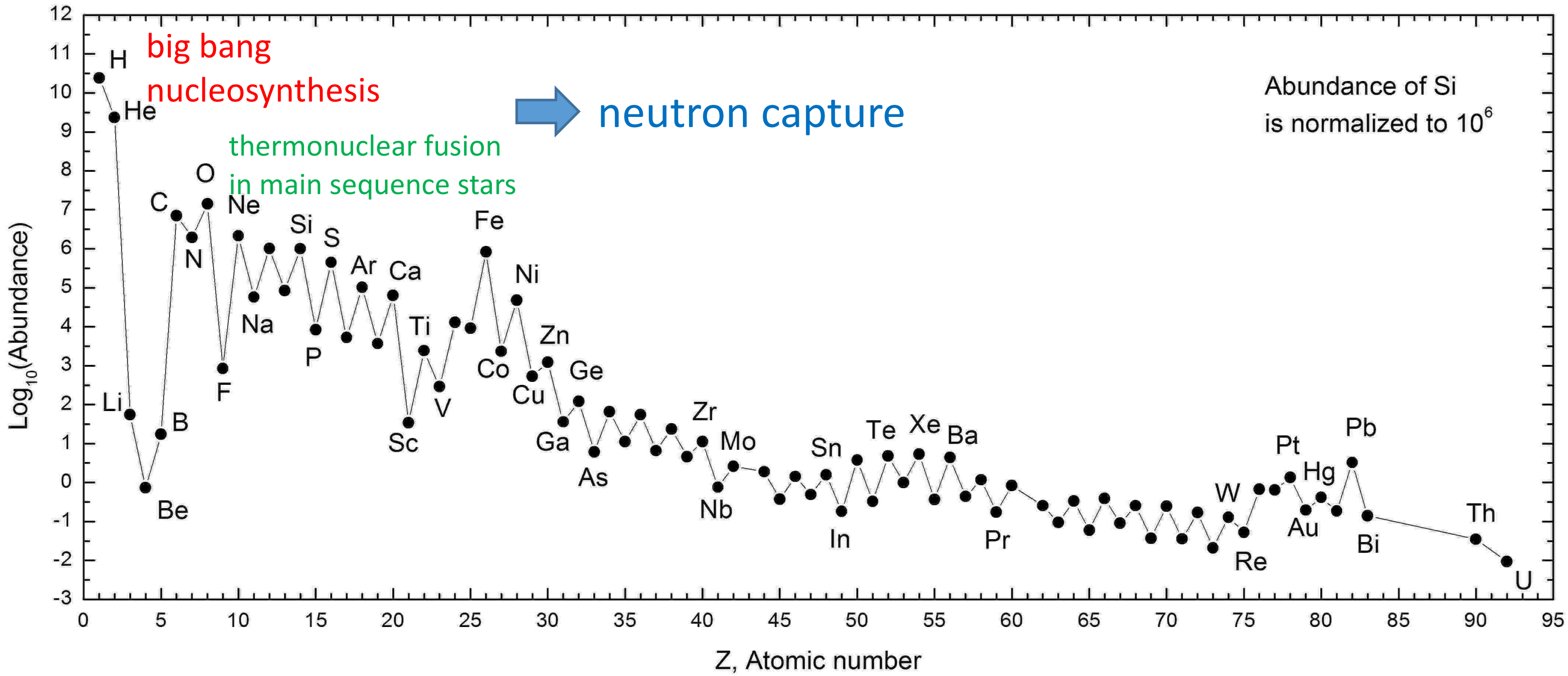
Talk Outline

- Gas giant atmospheres
- The transition to ‘metallic’ atmospheres
- Atmospheric escape processes
- Venus water loss and the runaway greenhouse
- Cold-trapping and climate on Mars (and Earth)
- Icy satellite / exomoon water loss
- Abiotic oxygen production on exoplanets


Sun
Gliese 229A
Teide 1
Gliese 229B
WISE1828
Jupiter
5,800 K
3,600 K
2,600 K
950 K
300–500 K
125 K
G2 star
red dwarf star
young brown dwarf
old brown dwarf
ultra-cool brown dwarf
planet

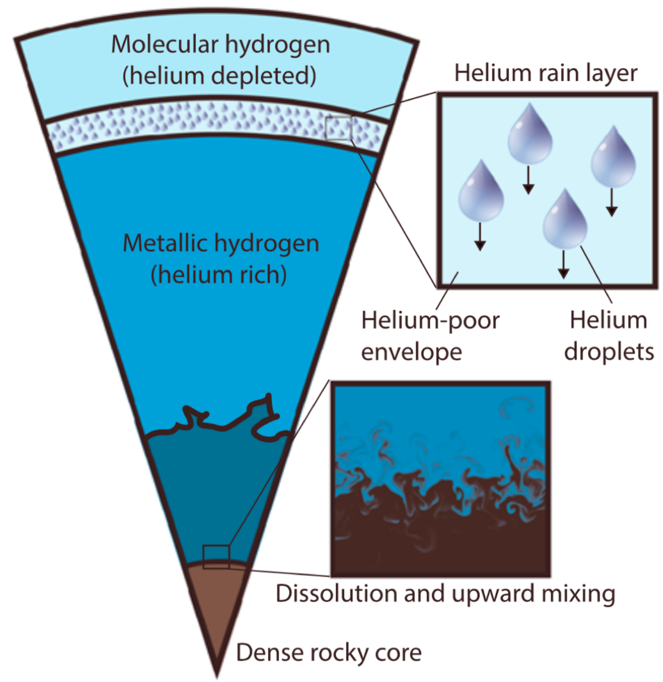
Elemental Abundances



https://upload.wikimedia.org/wikipedia/commons/7/70/SolarSystemAbundances.jpg

Gas Giant Planets

- Icy/rocky core formation, followed by capture of H_2/He envelope from nebula
- Core likely dissolves into envelope on Jupiter/Saturn subsequently: there are no solid boundaries anywhere (although maybe some layered convection)



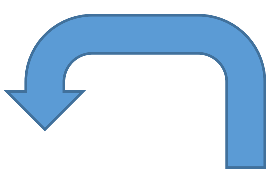
Wahl et al., 2017

https://oxfordre.com/planetaryscience/view/10.1093/acrefore/9780190647926.001.0001/acrefore-9780190647926-e-175

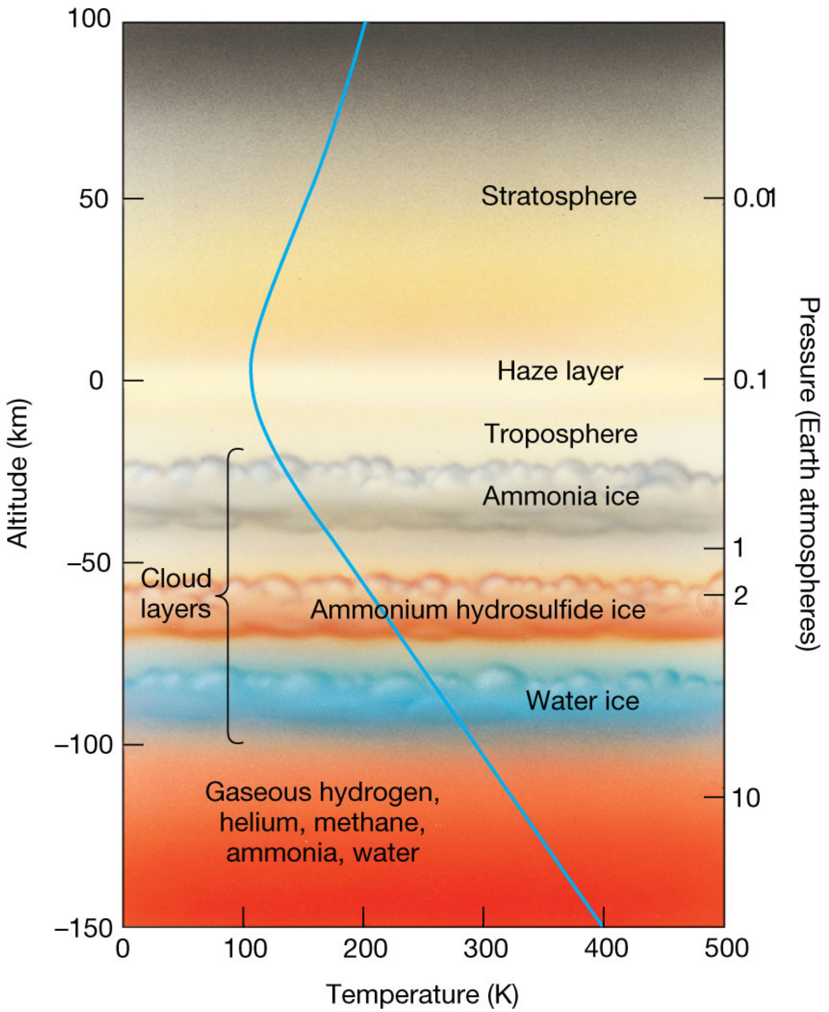
Gas Giant Planets

- H_2-dominated so in upper atmosphere equilibrium species are CH_4, H_2O, NH_3 etc.
- Modified by condensation processes
- Modified by photochemistry, e.g.

$CH_4 + h\nu \rightarrow C_2H_6 + 2H$ HIGH ATMOSPHERE



$C_2H_6 + H_2 \rightarrow 2CH_4$ **DEEP ATMOSPHERE**



Gas Giant Habitability:
A wonderful idea…

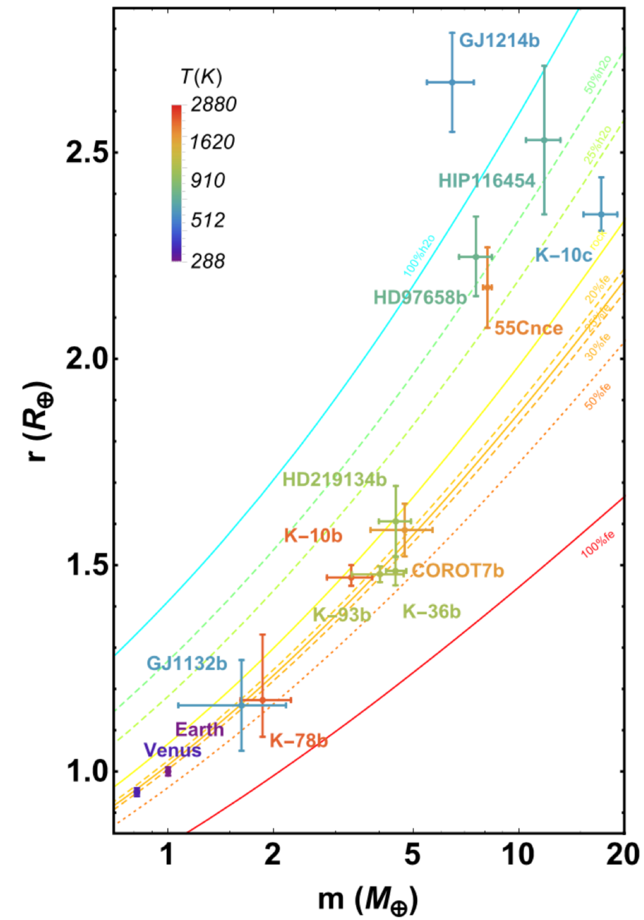
Adolf Schaller

Gas Giant Habitability: A wonderful idea… entirely unsupported by evidence

Adolf Schaller

The Rocky Planet Transition

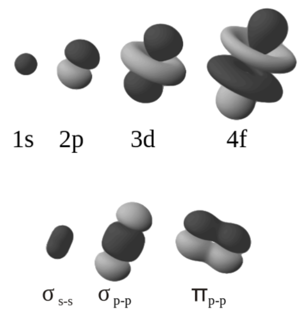
- Planets with radius > about 1.6 r_E usually retain a hydrogen envelope; those with smaller radii do not (e.g. Rogers, 2016)
- Transition corresponds to 5-10 M_E range
- Evolution of higher Z 'metallic' atmospheres is generally much more complex and nonlinear!



Zeng et al. 2016

Elemental Electronegativities

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \hat{H}\Psi(\mathbf{r},t)$$

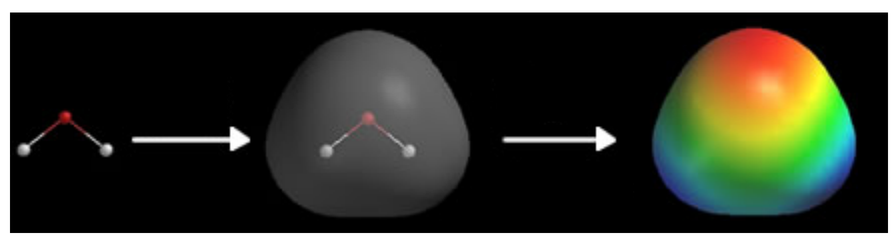


etc.

H 2.1																	He —
Li 1.0	Be 1.5											B 2.0	C 2.5	N 3.0	O 3.5	F 4.0	Ne —
Na 0.9	Mg 1.2											Al 1.5	Si 1.8	P 2.1	S 2.5	Cl 3.0	Ar —
K 0.8	Ca 1.0	Sc 1.3	Ti 1.5	V 1.6	Cr 1.6	Mn 1.5	Fe 1.8	Co 1.8	Ni 1.8	Cu 1.9	Zn 1.6	Ga 1.6	Ge 1.8	As 2.0	Se 2.4	Br 2.8	Kr —
Rb 0.8	Sr 1.0	Y 1.2	Zr 1.4	Nb 1.6	Mo 1.8	Tc 1.9	Ru 2.2	Rh 2.2	Pd 2.2	Ag 1.9	Cd 1.7	In 1.7	Sn 1.8	Sb 1.9	Te 2.1	I 2.5	Xe —
Cs 0.7	Ba 0.9	La–Lu 1.1–1.2	Hf 1.3	Ta 1.5	W 1.7	Re 1.9	Os 2.2	Ir 2.2	Pt 2.2	Au 2.4	Hg 1.9	Tl 1.8	Pb 1.8	Bi 1.9	Po 2.0	At 2.2	Rn —

Data from Linus Pauling. “The Nature of the Chemical Bond,” 3d ed., Cornell University Press, Ithaca, N.Y., 1960.

e.g. for H_2O:



https://en.wikipedia.org/wiki/Electronegativity#/media/File:Electrostatic_Potential.jpg

Oxidizing vs. reducing species

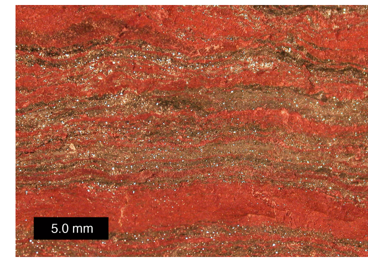
oxidation is loss of electrons, reduction is gain

Example:
$4Fe + 3O_2 \rightarrow 2Fe_2O_3$

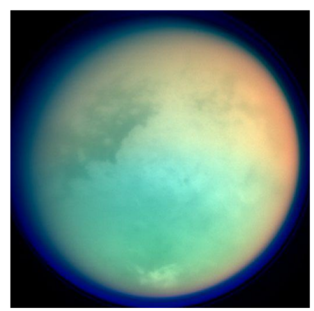
Fe electronegativity ~ 1.8
O electronegativity ~ 3.5

O oxidizes Fe from Fe^0 to Fe^{3+}

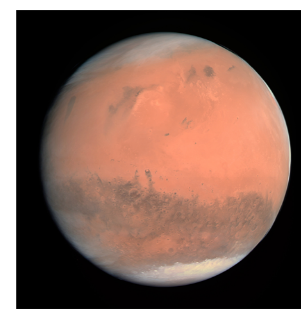
reduced iron (Fe^0)



oxidized iron (Fe^{3+})

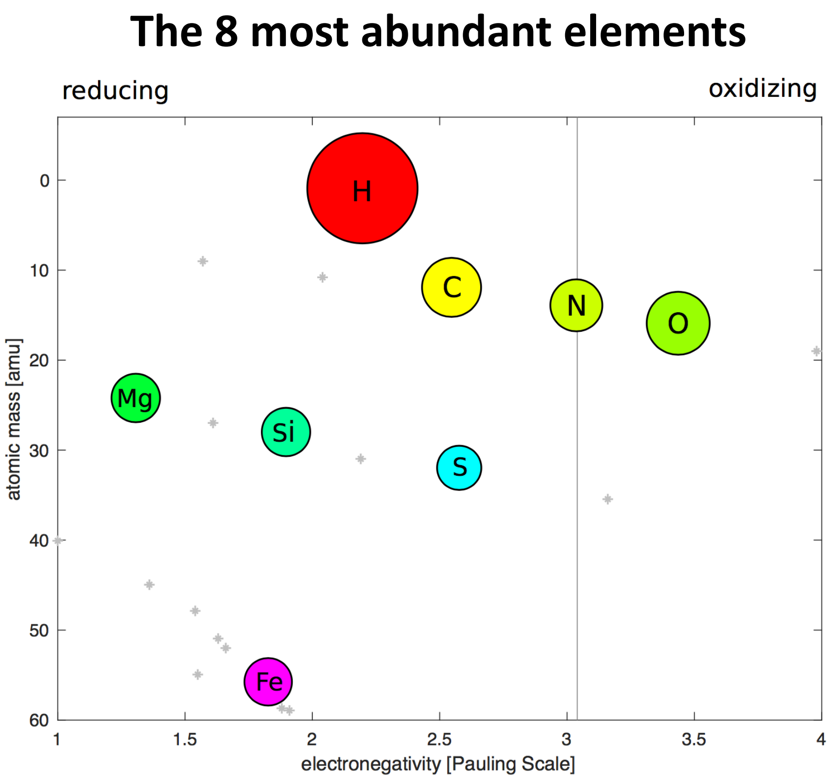


reduced surface (Titan)

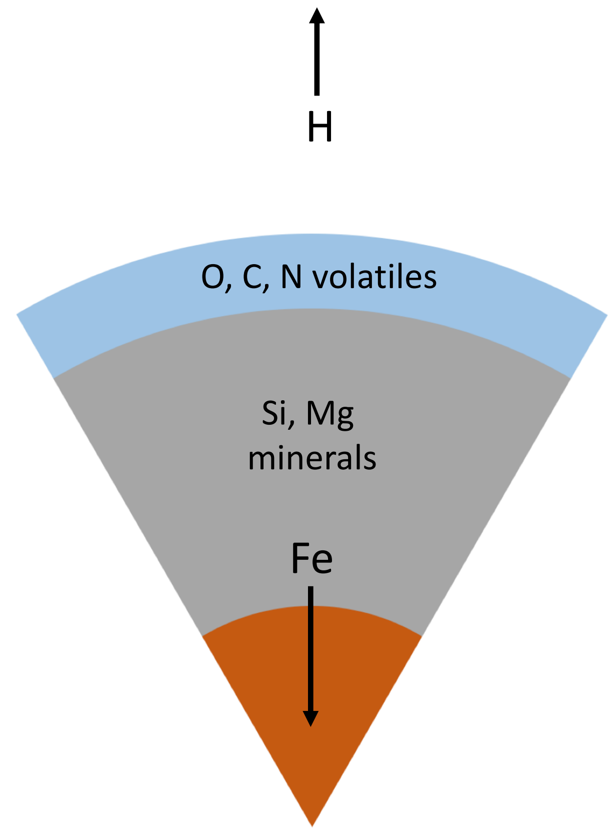


oxidized surface (Mars)

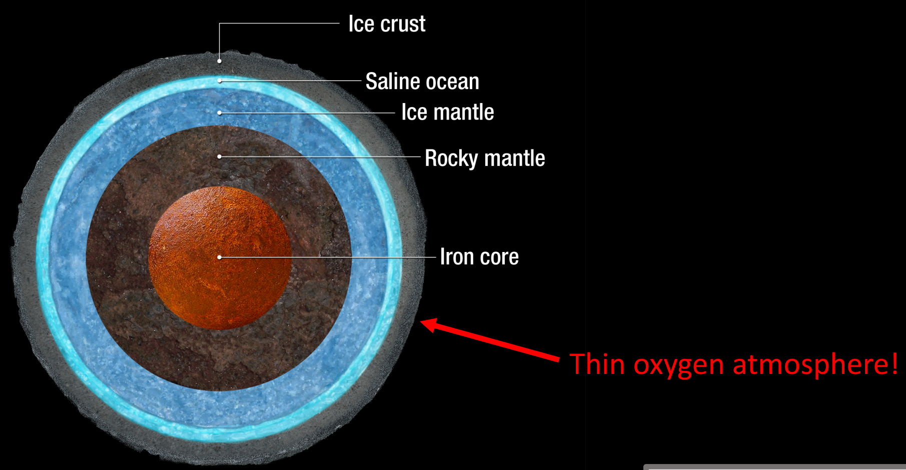
Galactic elemental abundances + gravity → oxidation of rocky/icy planet surfaces

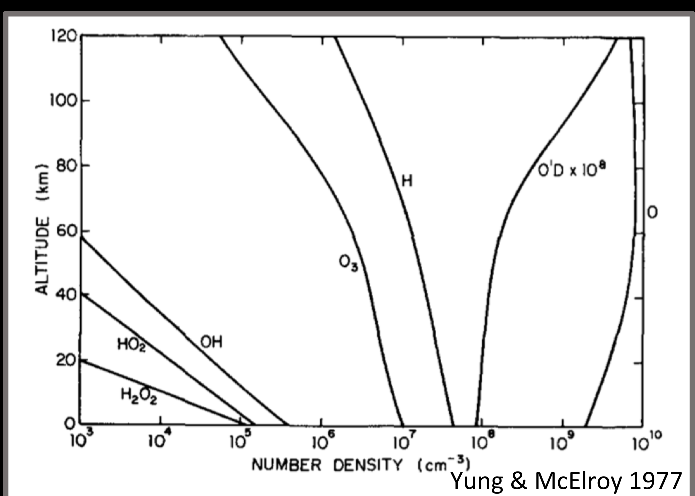


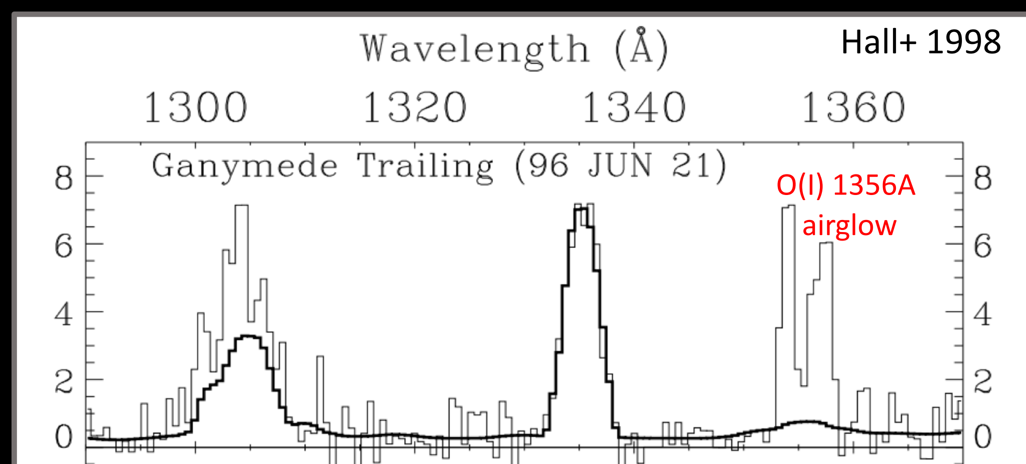
Wordsworth, Schaefer & Fischer, 2018



Ganymede





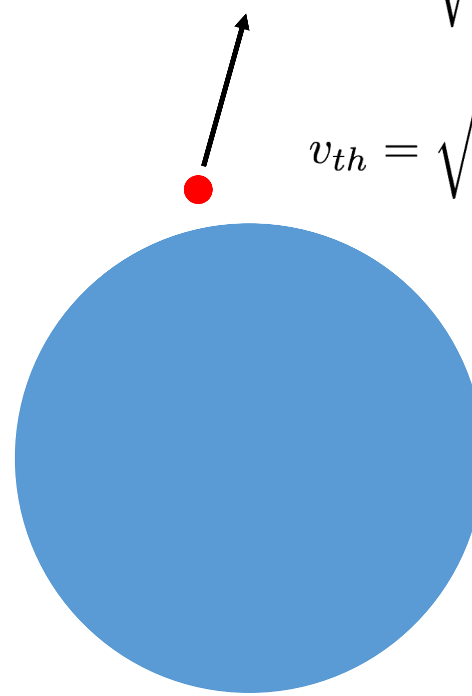


Quick quiz: Why is Titan so different?

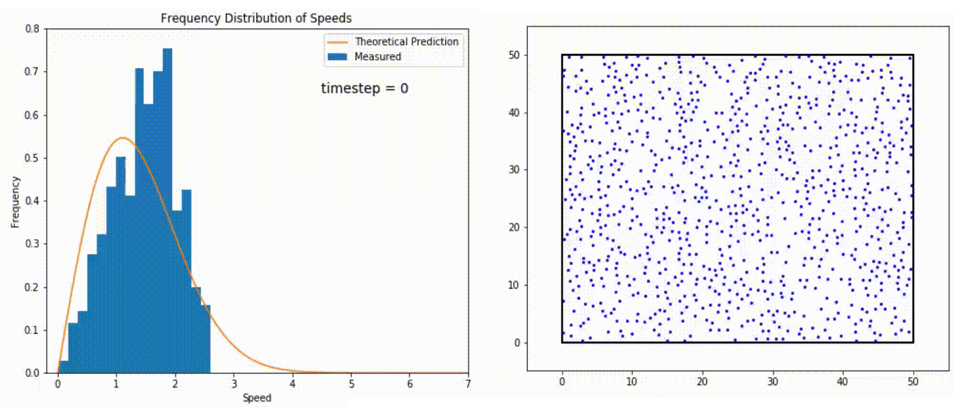
Physics of atmospheric escape

- Can start by thinking about escape velocity of individual gas molecule
- Compare with thermal velocity to get escape parameter χ
- Jeans escape for high χ values

$$v_e = \sqrt{\frac{2GM}{r}}$$



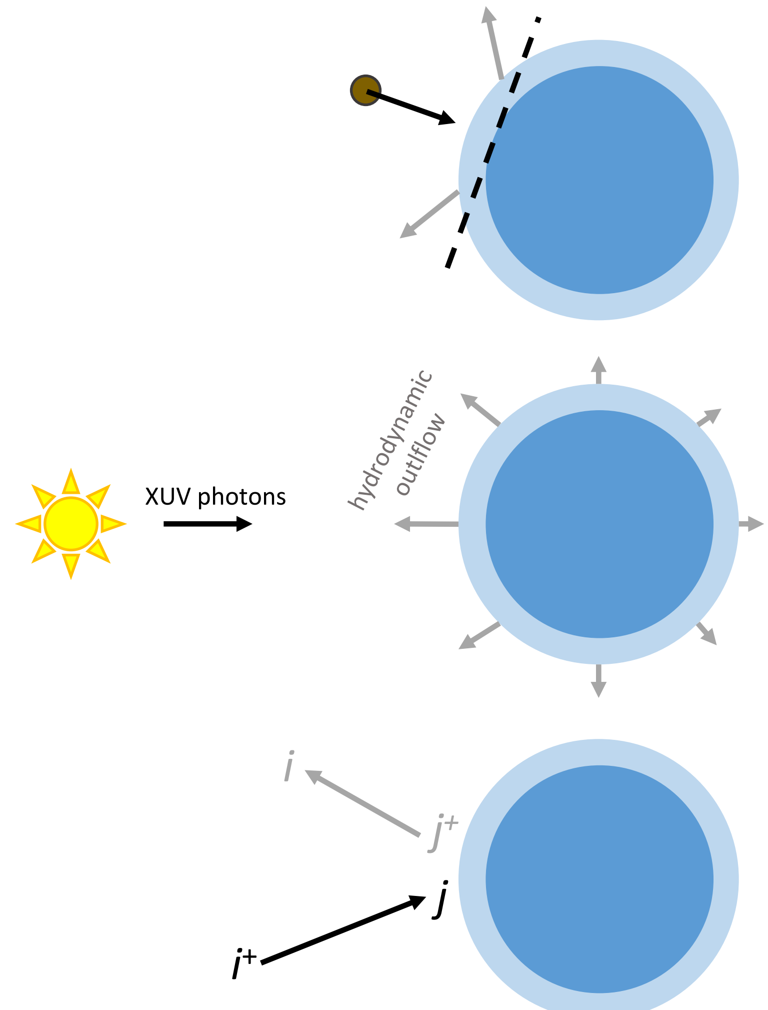
$$v_{th} = \sqrt{\frac{2k_BT}{m}}$$



$$\chi = \frac{v_e^2}{v_{th}^2} = \frac{GMm/r}{k_BT} = \frac{mgr}{k_BT} = \frac{r}{H}$$

Key atmospheric escape processes

- **Impact-driven escape**: Hydrodynamic blowaway of atmosphere by bolide impacts. Net atmospheric loss only under certain conditions.
- **XUV-driven hydrodynamic escape**: High-energy stellar photons power outflow. A major player early on (we think!)
- **Non-thermal processes**: Varied, complex, generally most important for elements heavier than He



Key atmospheric escape processes

- **Impact-driven escape**: Hydrodynamic blowaway of atmosphere by bolide impacts. Net atmospheric loss only under certain conditions.
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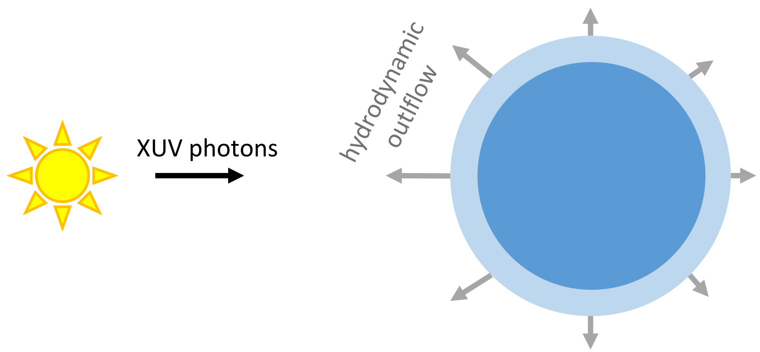
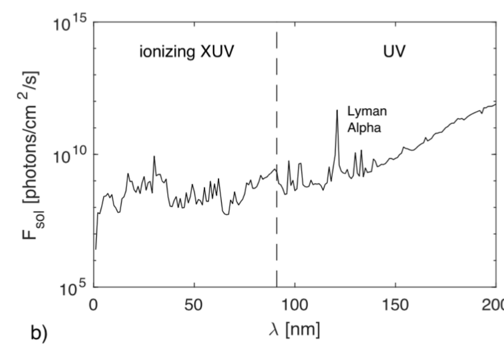
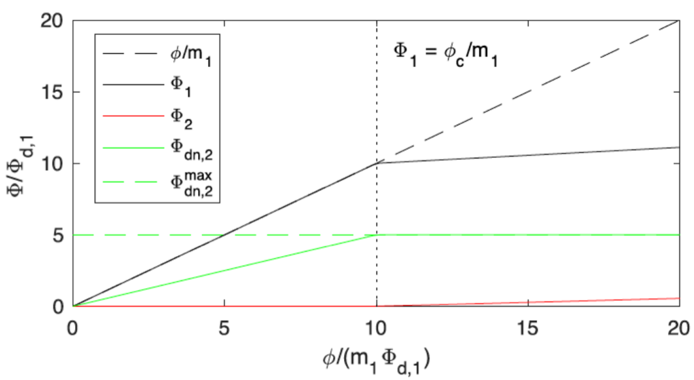
$$\phi_E = \frac{\epsilon F_{\rm XUV}}{4 V_{\rm pot}}$$





Hydrodynamic drag of heavier species

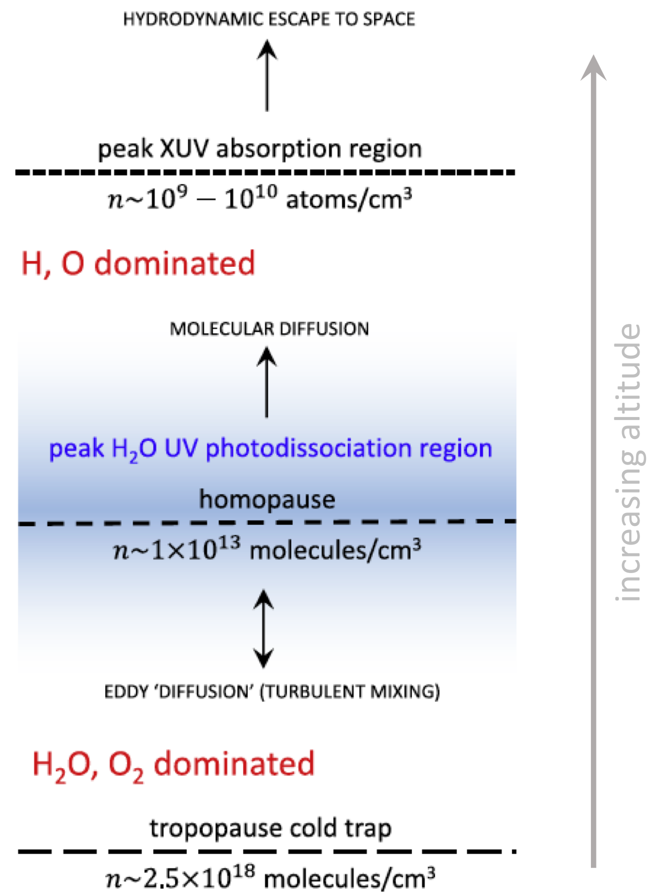
- Planetary upper atmospheres are not well-mixed: lighter species expand upwards above the homopause
- Nonetheless, for a high enough H escape flux, heavier species can be dragged along too during XUV-driven escape



Significantly less of the heavier species escapes

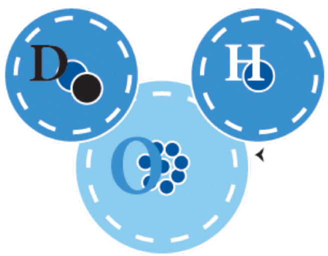
$$\Phi_1 \approx \begin{cases} \phi/m_1 & : \phi < \phi_c \\ [x_1\phi + x_1x_2(m_2 - m_1)\Phi_{d,2}]/\overline{m} & : \phi \geqslant \phi_c \end{cases} \qquad \phi_c = \frac{bx_1}{H_1}(m_2 - m_1)$$

$$\Phi_2 \approx \begin{cases} 0 & : \phi < \phi_c \\ [x_2\phi + x_1x_2(m_1 - m_2)\Phi_{d,1}]/\overline{m} & : \phi \geqslant \phi_c. \end{cases} \qquad \Phi_{d,i} \equiv \frac{b}{H_i}$$

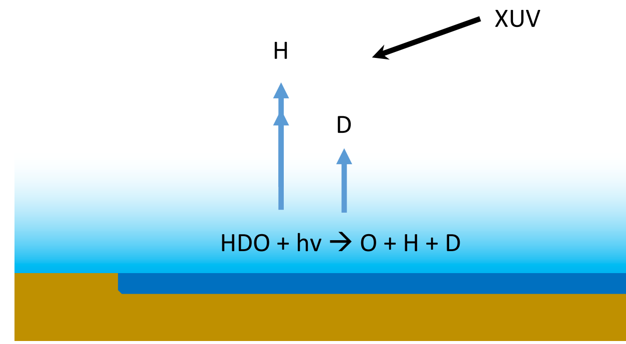


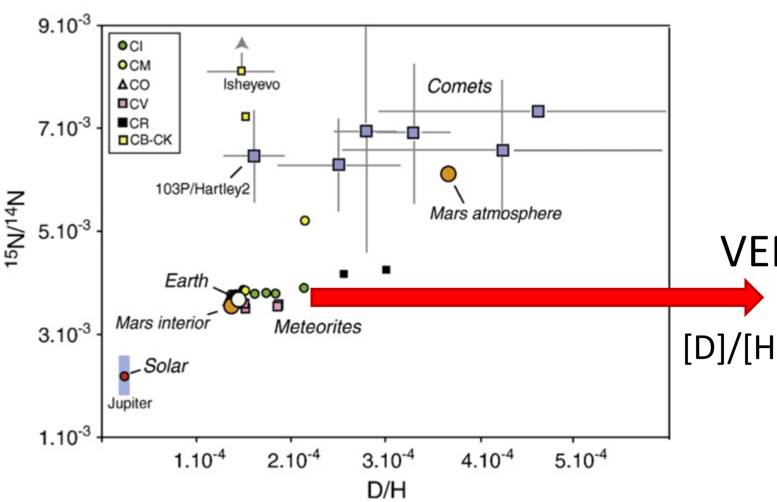
Wordsworth, Schaefer & Fischer 2018

Enriched deuterium: a smoking gun for past atmospheric escape?



HDO
(heavy water)

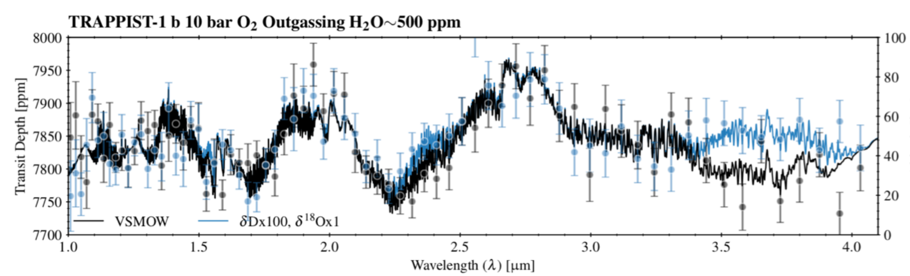




VENUS

[D]/[H] ~ 0.016

Marty 2012

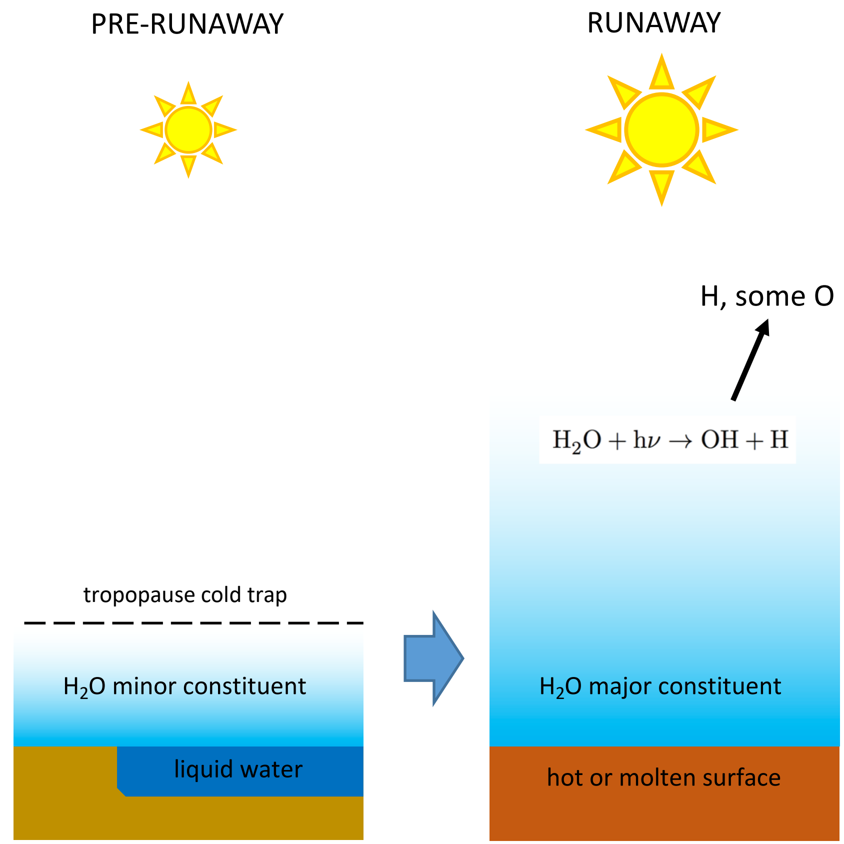


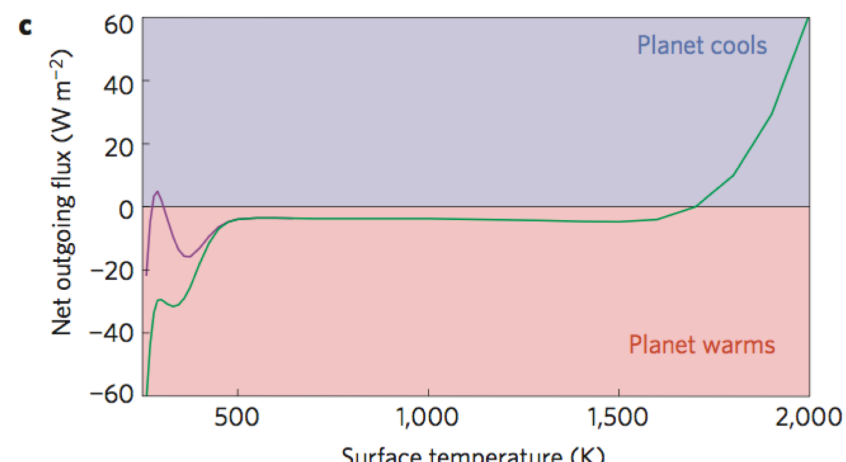
Lincowski et al. 2019 [see also Mollière & Snellen, 2019]

https://www.usgs.gov/media/images/heavy-ice

Venus Water Loss

- Habitable early Venus… maybe up to 0.7 Ga? (e.g. Way et al. 2016)
- Then, runaway greenhouse event
  - Oceans boil off, H_2O reaches high atmosphere, photolyzes, and H is lost to space
- But where is the oxygen? Most escape models indicate substantial amounts should be left behind (e.g. Kasting & Pollack, 1983)

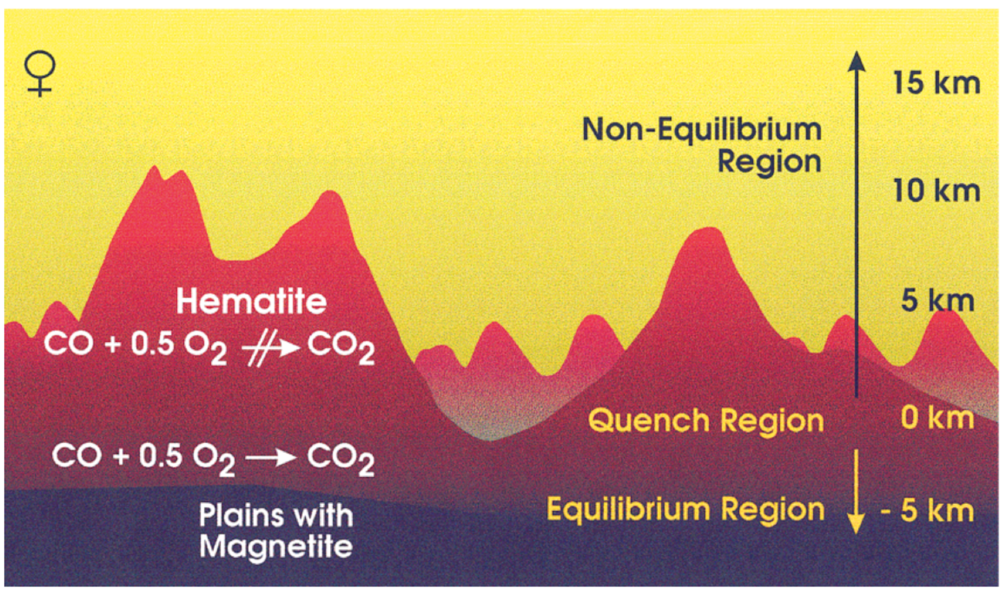




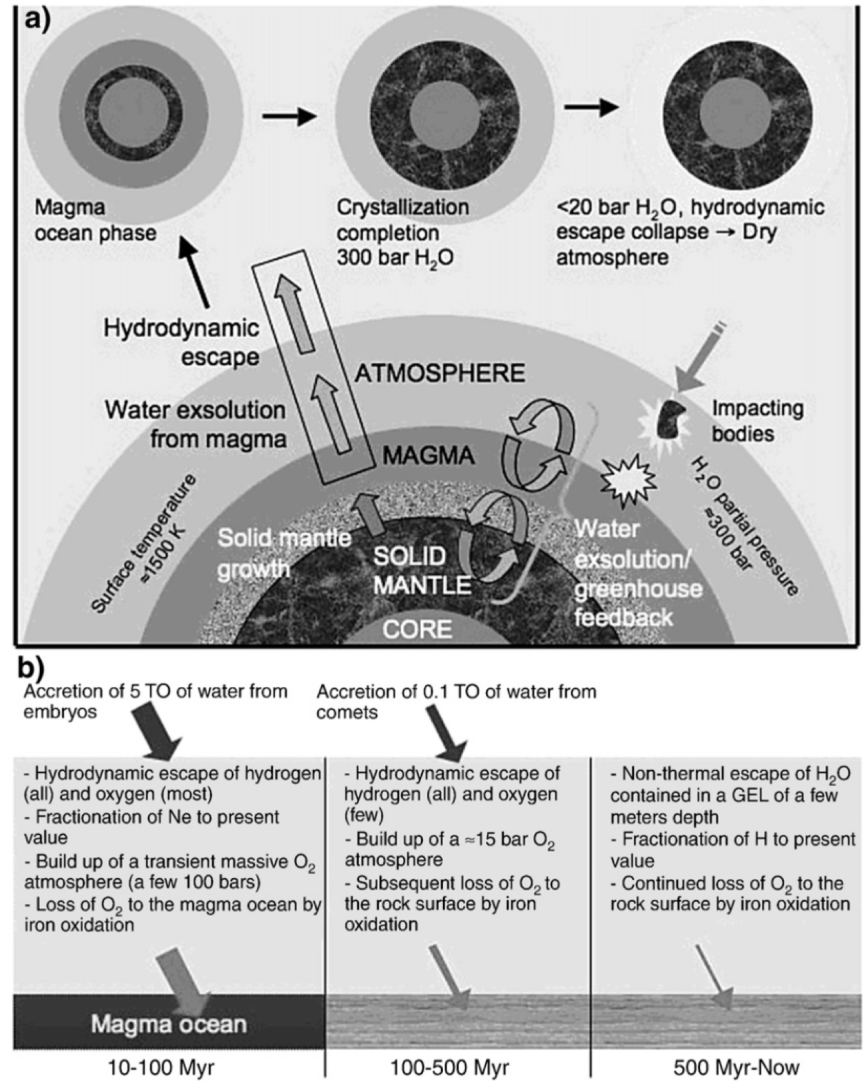
Goldblatt+ (2013)

Venus Water Loss

- Another possibility: early magma ocean phase
- Fits noble gas isotopic ratios, estimated surface / interior oxidation state

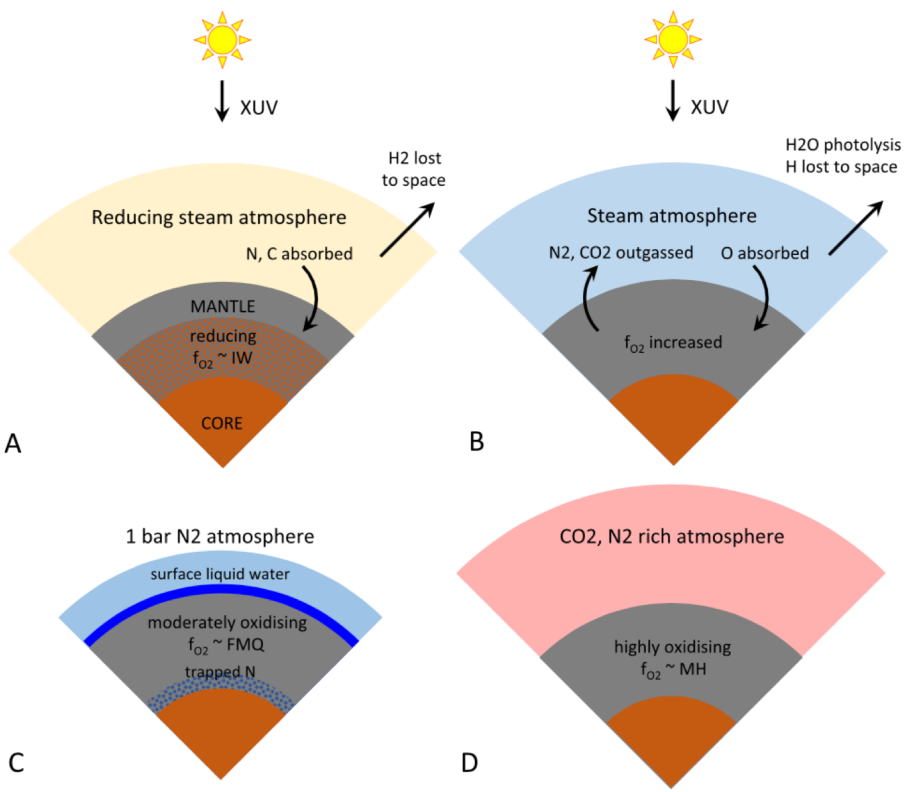


Fegley et al. (1997)

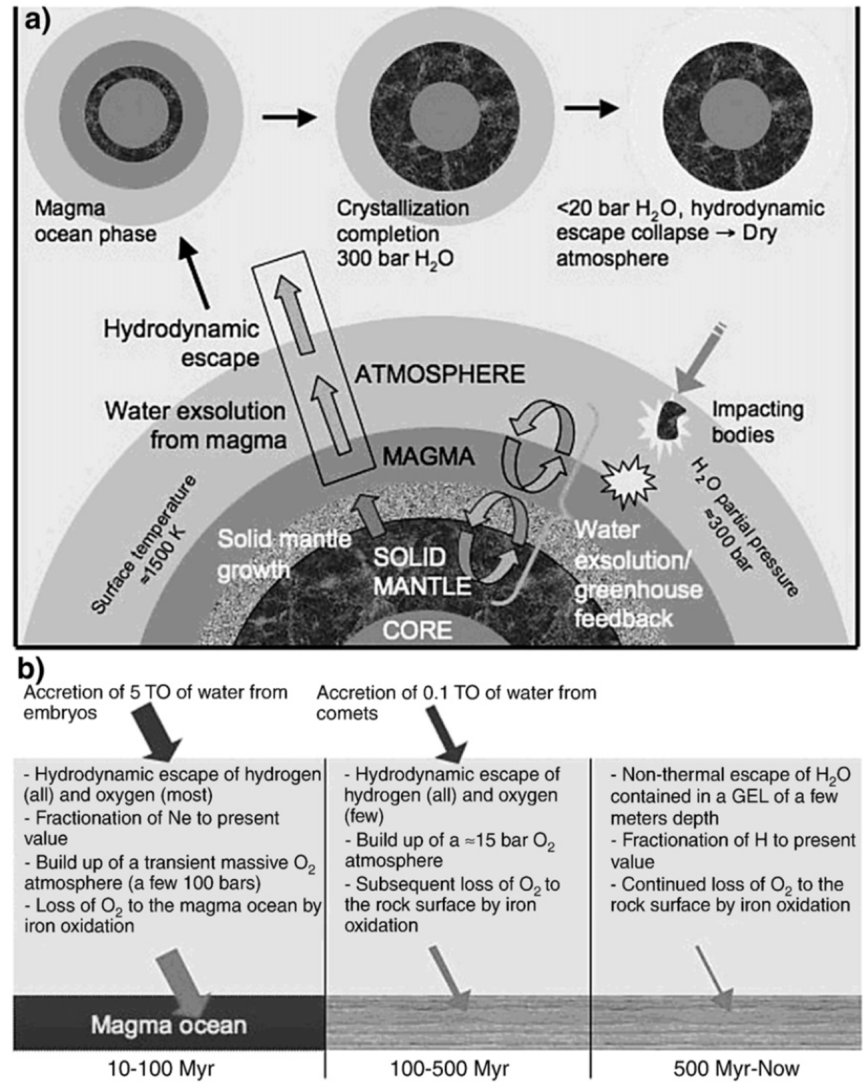


Gillmann et al. (2009)

Venus Water Loss



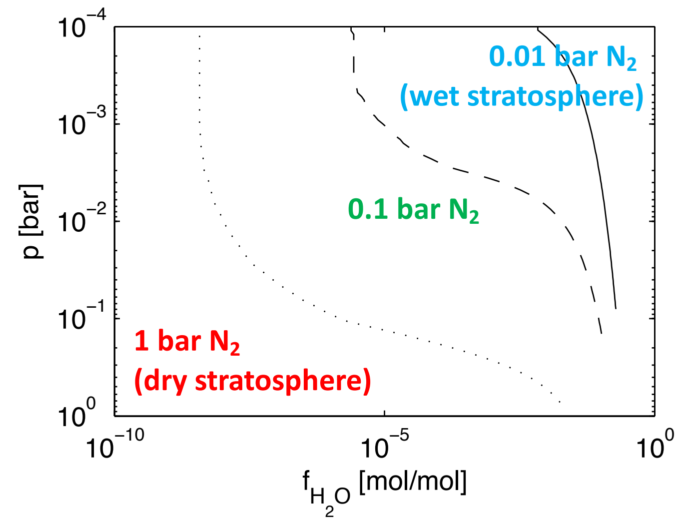
Wordsworth 2016, EPSL



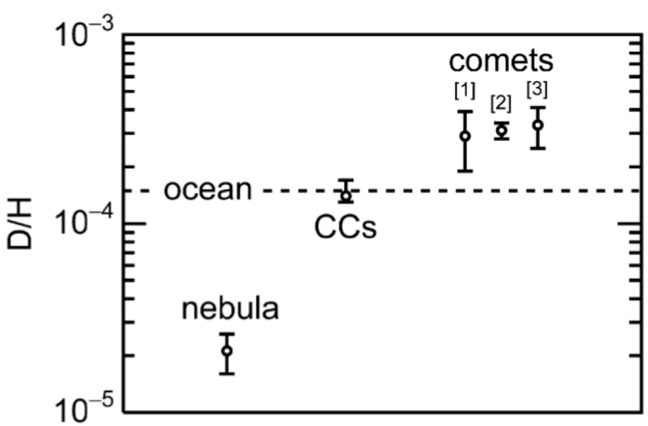
Gillmann et al. (2009)

Earth Water Loss

- Current 1 bar atmosphere keeps H_2O *cold-trapped* in the troposphere
- Stratosphere remains dry, very little hydrogen is lost
- Was this always the case?
- What role did H_2/CH_4 loss play?



Wordsworth & Pierrehumbert (2014)



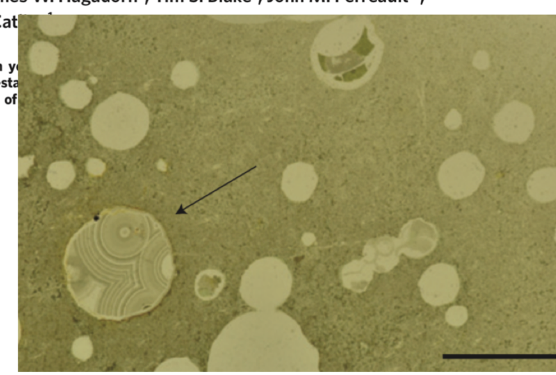
Genda & Ikoma (2008) [see also Zahnle et al. 2018]

nature geoscience LETTERS
PUBLISHED ONLINE: 9 MAY 2016 | DOI: 10.1038/NGEO2713

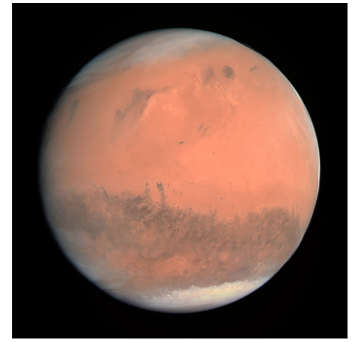
Earth's air pressure 2.7 billion years ago constrained to less than half of modern levels

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. Cat

How the Earth stayed warm several billion y
the Sun was considerably fainter is the long-sta
of the 'faint young Sun paradox'. Because of

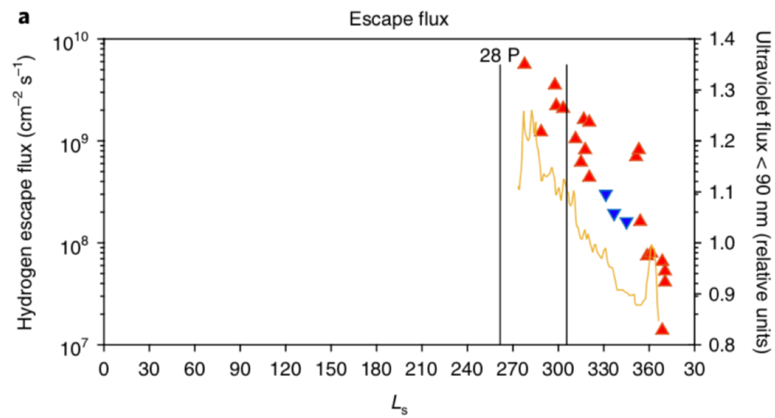


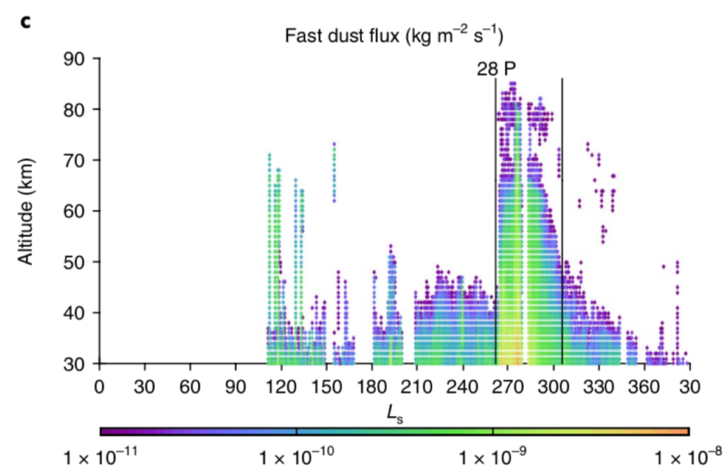
Mars Water Loss



MSL rover drill core

- H_2O is also generally cold-trapped (thinner atmosphere, but colder surface)
- In addition, photochemical feedbacks prevent oxidation when H_2O photolysed in lower atmosphere
- However, this can be circumvented by intense H_2O lofting events during dust storms (Chaffin et al. 2017; Heavens et al. 2018)
- D/H ratio suggests early H_2O inventory was several times greater than today
- Early Martian atmosphere could have been more reducing, with possible climate implications (e.g. Wordsworth et al. 2013; Ramirez et al. 2014; Batalha et al. 2016)

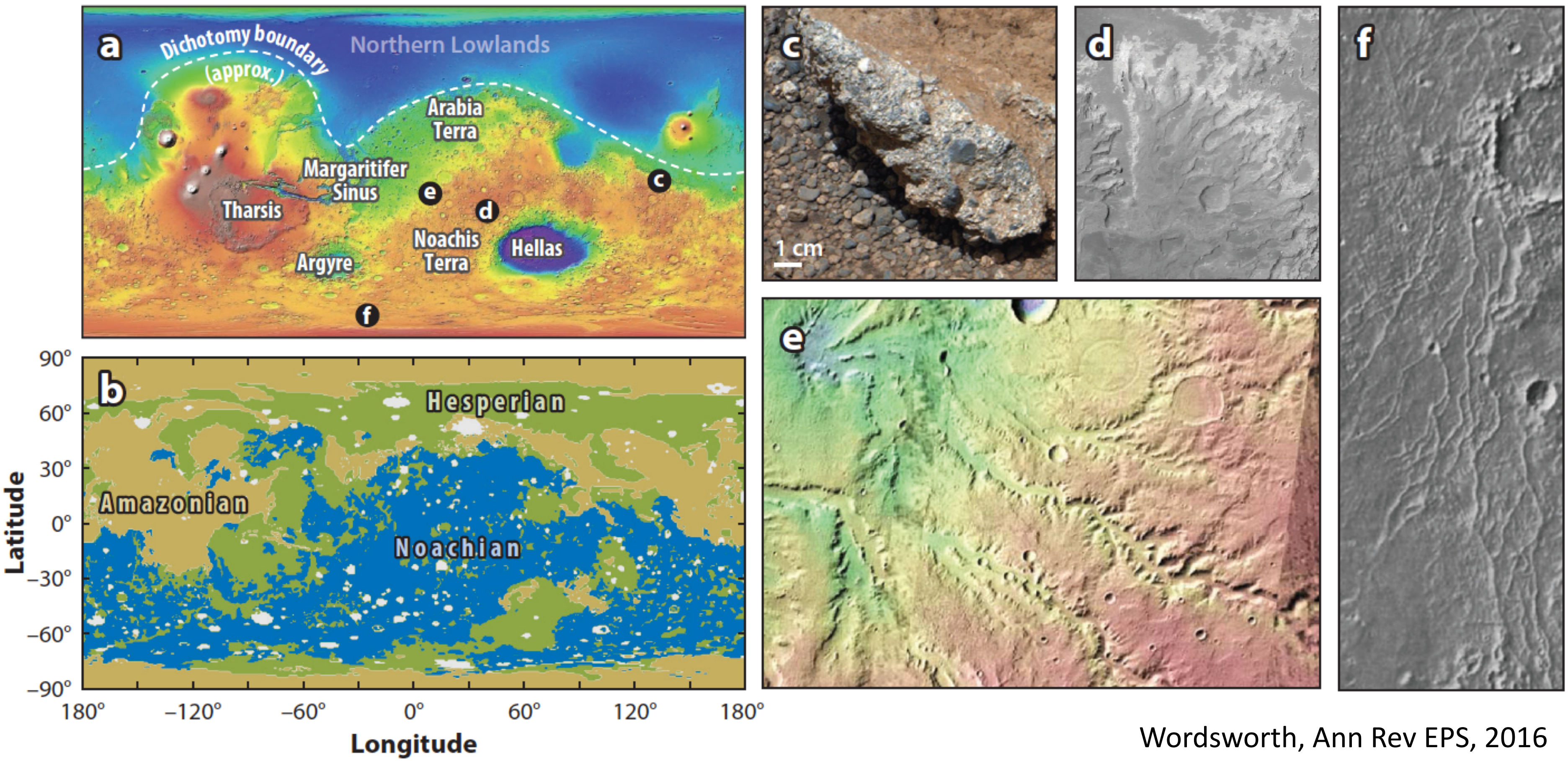




http://photojournal.jpl.nasa.gov/catalog/PIA16834
https://www.pnnl.gov/science/highlights/highlight.asp?id=871

Heavens et al., 2018

Flowing water on early Mars



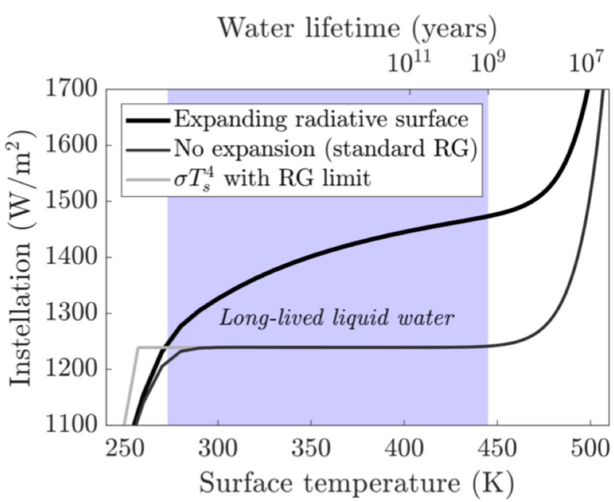
Wordsworth, Ann Rev EPS, 2016

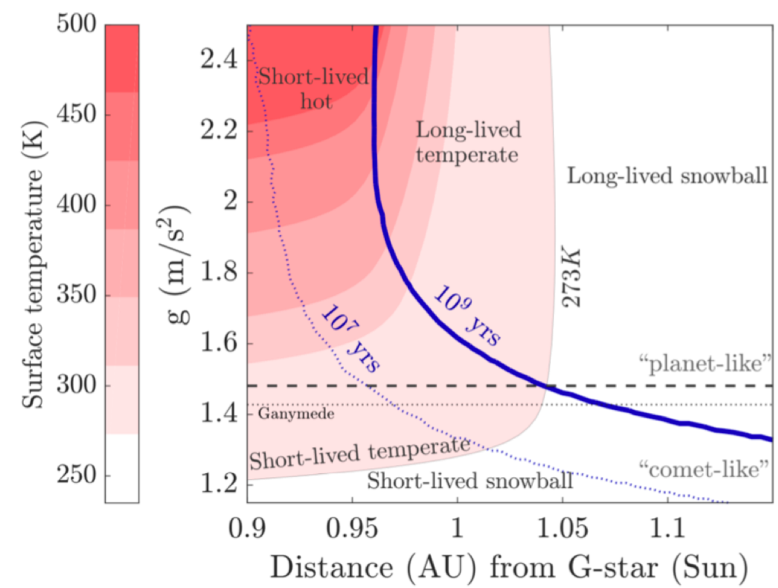
Data from: Tanaka 1986; Scott & Tanaka 1986; Tanaka & Scott 1987; Williams et al. 2013; Malin & Edgett 2003; Howard et al. 2005; Head & Pratt 2001

Amazonian: 0-3 Ga
Hesperian: 3-3.5 Ga
Noachian: More than 3.5 Ga

Hydrodynamic Water Loss from Icy Satellites / Exomoons

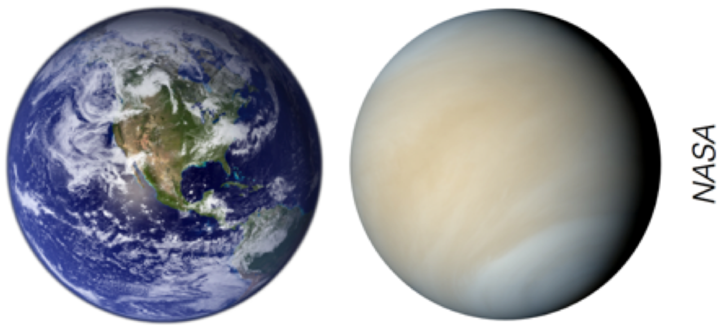
?

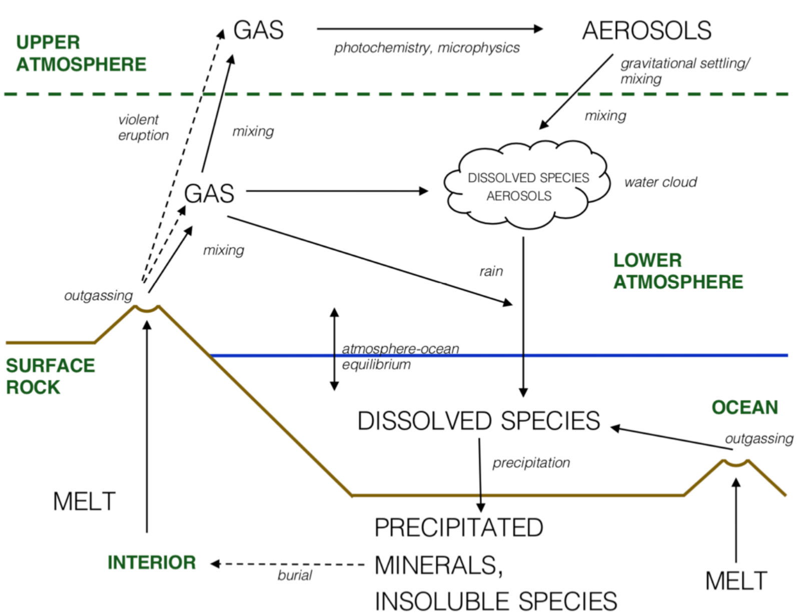


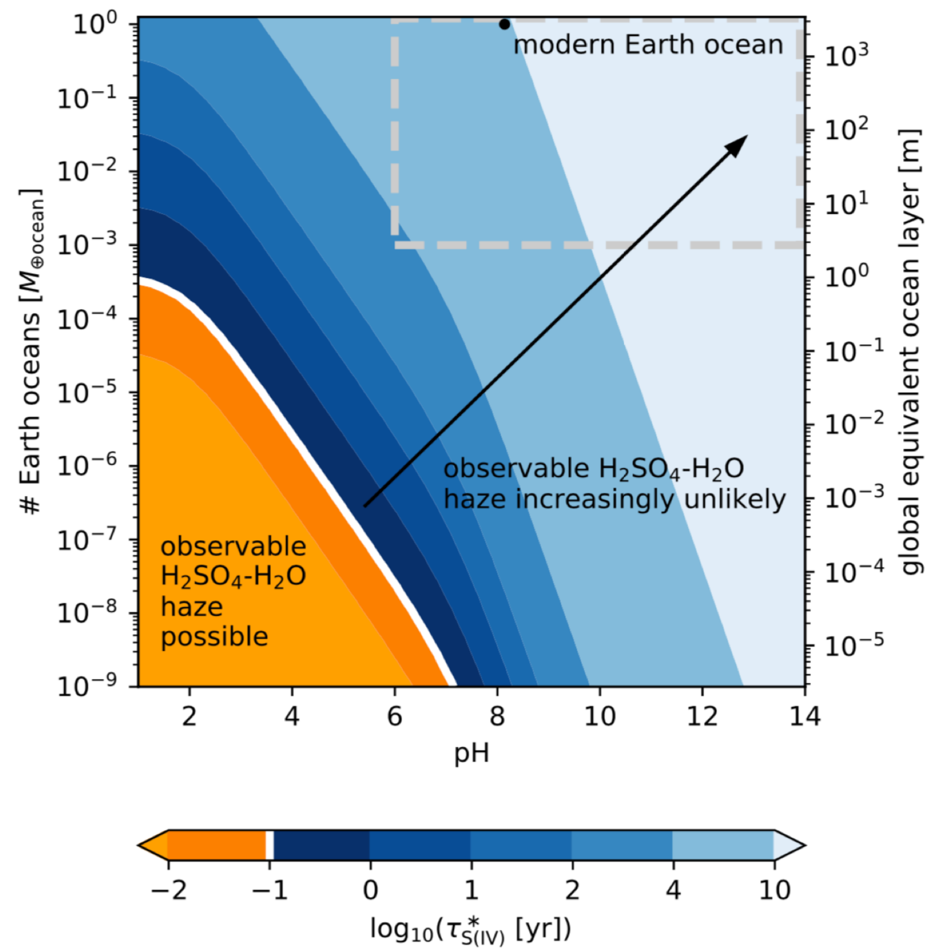


Arnscheidt, Wordsworth & Ding, 2019
[see also Goldblatt, 2015 and Lehmer et al. , 2017]

Using Atmospheric Sulfur to Diagnose Surface Liquid Water



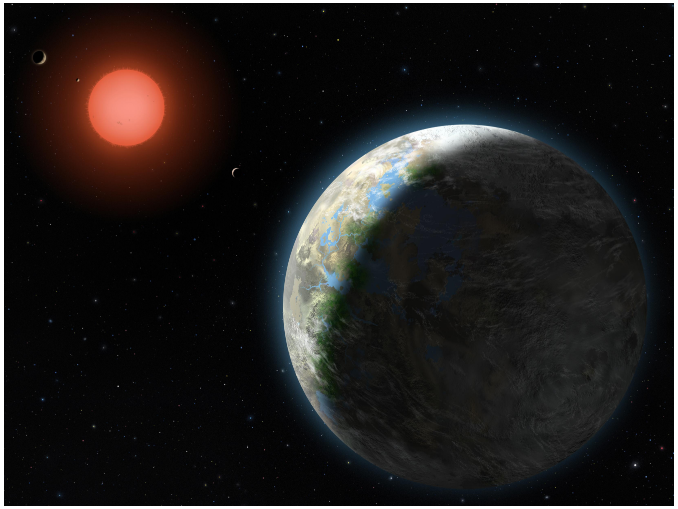


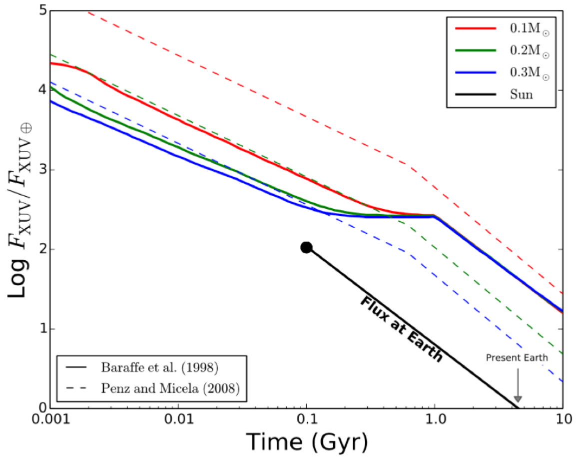


Loftus, Wordsworth & Morley, in prep, 2019

How far could water loss and abiotic O_2 buildup proceed on exoplanets?

- M-stars have an extended pre-main sequence phase
- M-stars have high XUV levels, stellar activity → enhanced atmospheric loss (likely including heavy gases like N_2)
- M-star planets should suffer significant H loss + oxidation
- Will planets around them develop abiotic O_2 atmospheres?

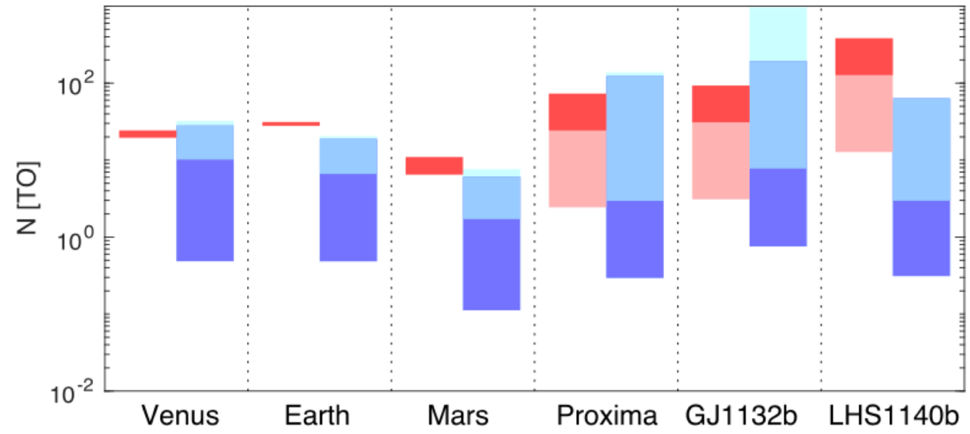


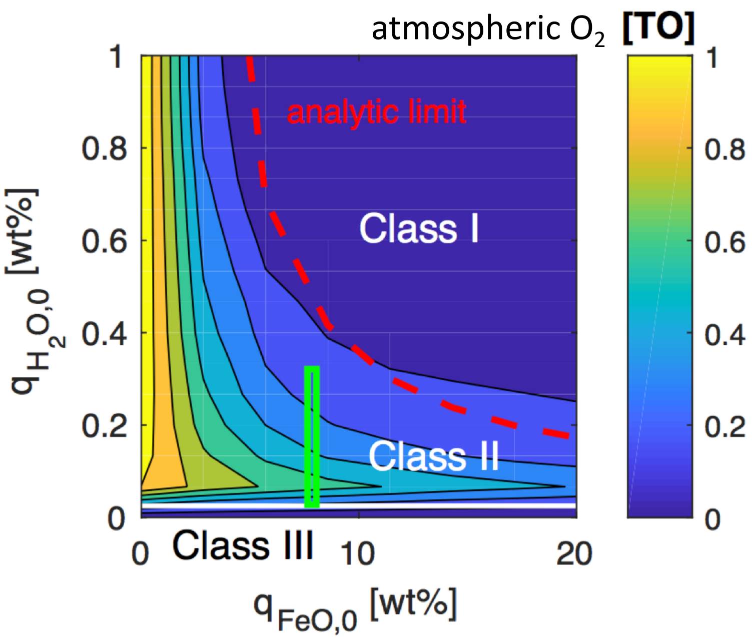


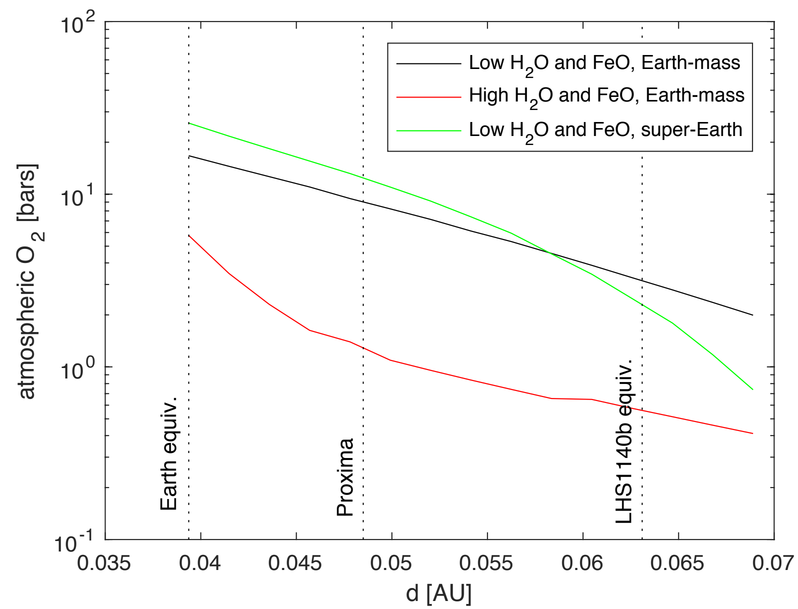
Luger & Barnes 2016

How far could water loss and abiotic O_2 buildup proceed on exoplanets?

total potential oxidation via water loss
plausible mantle FeO range



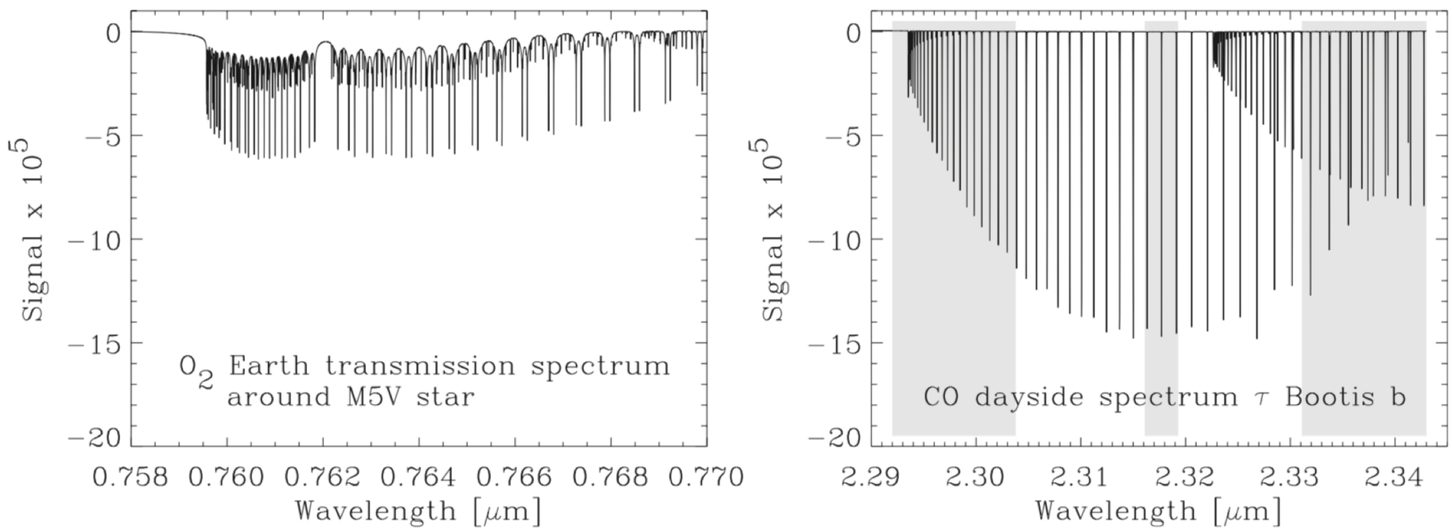




Wordsworth, Schaefer and Fischer, 2018

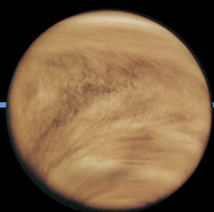
How far could water loss and abiotic O_2 buildup proceed on exoplanets?

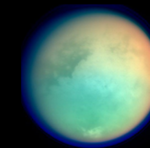
Planet	Abiotic O_2 buildup potential	Remarks
Prox Cen b	MEDIUM	Low received stellar flux, Earth-like mass.
GJ1132b	HIGH	High stellar flux: planet is likely sterile.
LHS1140b	LOW	Low stellar flux, high planet mass.
TRAPPIST-1b	MEDIUM	High stellar flux: planet is likely sterile.
TRAPPIST-1c	MEDIUM	High stellar flux.
TRAPPIST-1d	MEDIUM	Moderate stellar flux.
TRAPPIST-1e	MEDIUM	Moderate stellar flux.
TRAPPIST-1f	LOW	Low stellar flux.
TRAPPIST-1g	LOW	Low stellar flux.

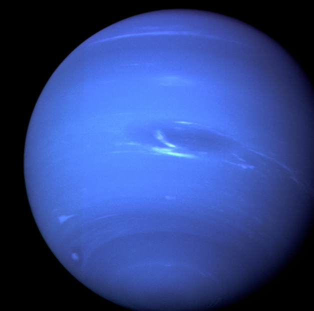


Snellen et al. 2013

A Redox Goldilocks Zone







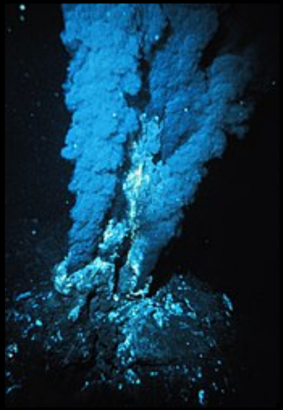
OVER-OXIDIZED

Both oxidized and reduced surface/atmosphere reservoirs

UNDER-OXIDIZED

Fertile conditions for biogenesis…

? ? ?



Conclusions

- Gas giant atmospheres are not in chemical equilibrium, but dilution makes them poor places to search for life
- Rocky planet atmospheres tend to be out of chemical equilibrium and relatively oxidized in galactic terms because H escapes to space and Fe sinks to the core, leaving O-rich volatile species at the surface
- Venus and Mars both underwent extensive water loss + surface oxidation. Earth perhaps underwent less, thanks to its efficient N_2 cold trap, but questions remain.
- Extreme oxidation may occur on many Earth-like exoplanets. This has major implications for false biosignatures and for the likelihood of prebiotic chemistry / biogenesis

Impact-Generated Atmospheres over Titan, Ganymede, and Callisto

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The competition between impact erosion and impact supply of volatiles to planetary atmospheres can determine whether a planet or satellite accumulates an atmosphere. In the absence of other processes (e.g., outgassing), we find either that a planetary atmosphere should be thick, or that there should be no atmosphere at all. The boundary between the two extreme cases is set by the mass and velocity distributions and intrinsic volatile content of the impactors. We apply our model specifically to Titan, Callisto, and Ganymede. The impacting population is identified with comets, either in the form of stray Uranus–Neptune planetesimals or as dislodged Kuiper belt comets. Systematically lower impact velocities on Titan allow it to retain a thick atmosphere, while Callisto and Ganymede get nothing. Titan's atmosphere may therefore be an expression of a late-accreting, volatile-rich veneer. An impact origin for Titan's atmosphere naturally accounts for the high D/H ratio it shares with Earth, the carbonaceous meteorites, and Halley. It also accounts for the general similarity of Titan's atmosphere to those of Triton and Pluto, which is otherwise puzzling in view of the radically different histories and bulk compositions of these objects.

velocities of incident material. Because Saturn is less massive than Jupiter, and because Jupiter sits deeper in the Sun's gravitational well, the average impact velocity of stray bodies striking Titan is lower than those striking Callisto or Ganymede. Other things being equal, the lower impact velocity allows Titan t
of incoming atmophiles, and t
erosion, than its Jovian count
will want to address here is wh
could suffice to account for th

2. ATMOSPHERIC

Atmospheric cratering (a.k.a
the expulsion of atmospheric ga
suggested, in diverse forms an
important loss process for pla
terrestrial planets (Cameron 19
1986, Ahrens and O'Keefe 1
Ahrens *et al.* 1989, Hunten *et a*