Mars, the Faint Young Sun Problem and Human Exploration

R. Wordsworth

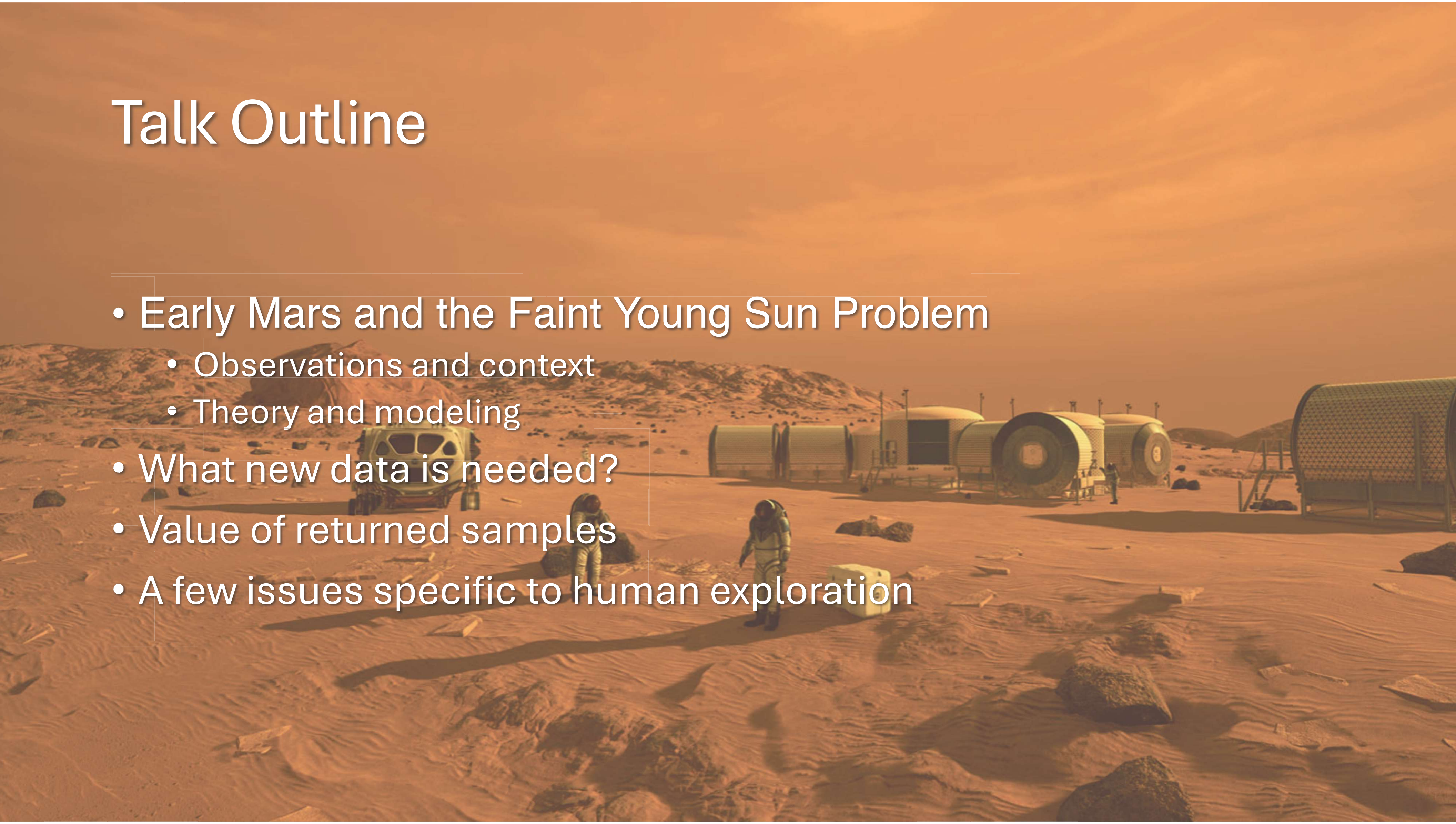
NASEM Study on Human Mars Science

Panel on Atmospheric Science and Space Physics

Open Session

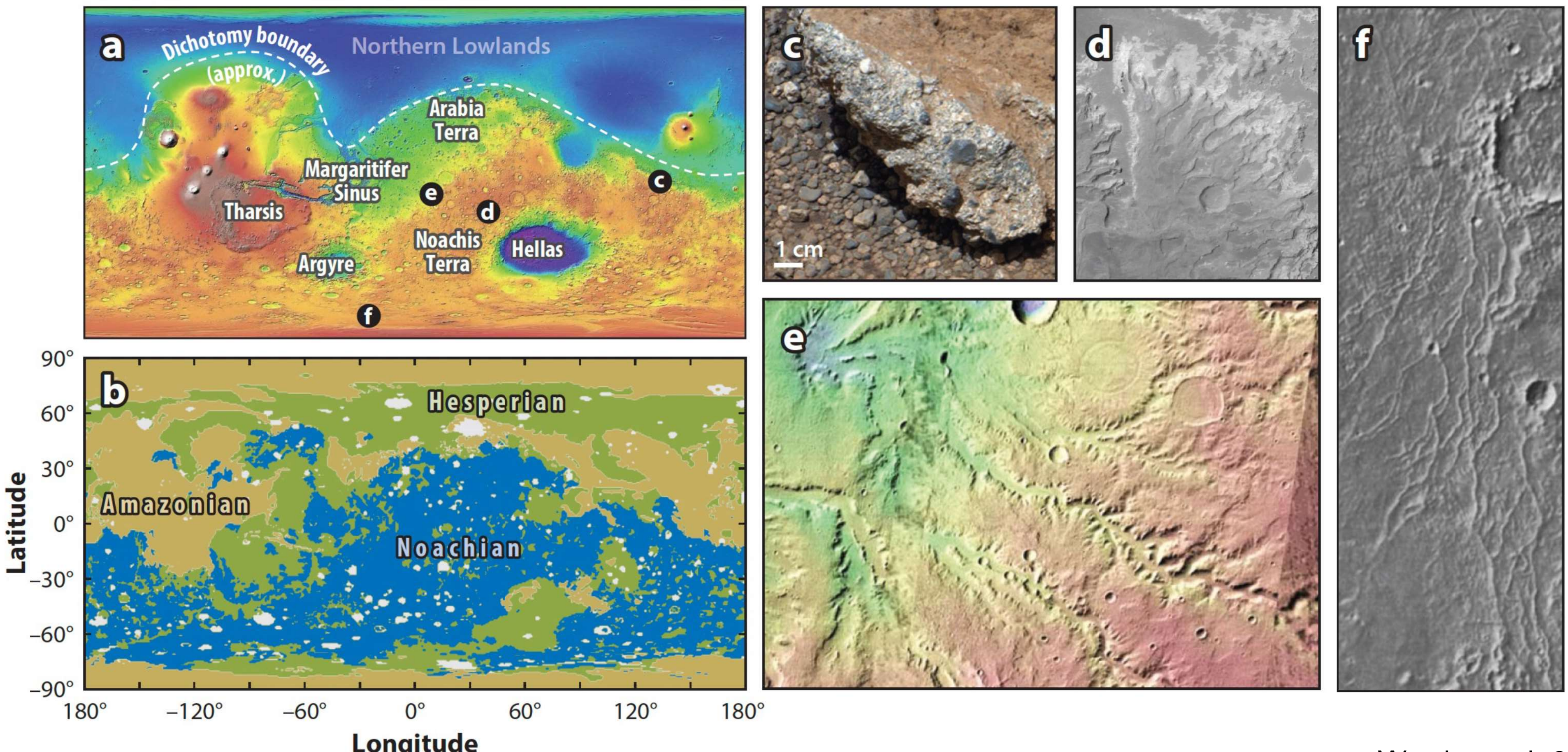
Tuesday July 30, 2024

Talk Outline



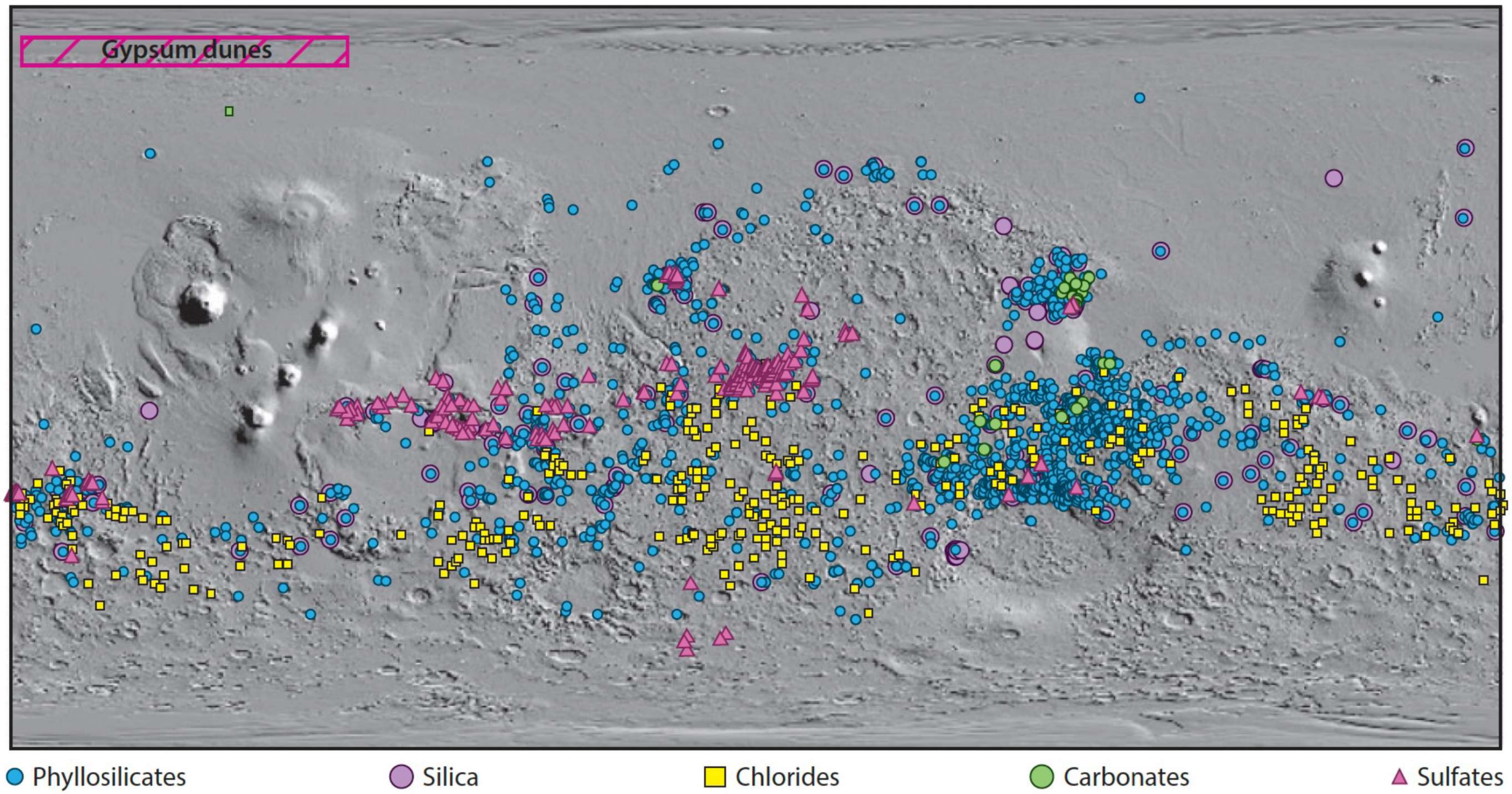
- Early Mars and the Faint Young Sun Problem
  - Observations and context
  - Theory and modeling
- What new data is needed?
- Value of returned samples
- A few issues specific to human exploration

Early Mars: A Planet Sculpted by Water



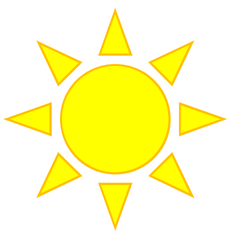
Wordsworth 2016

Early Mars: A Planet Sculpted by Water

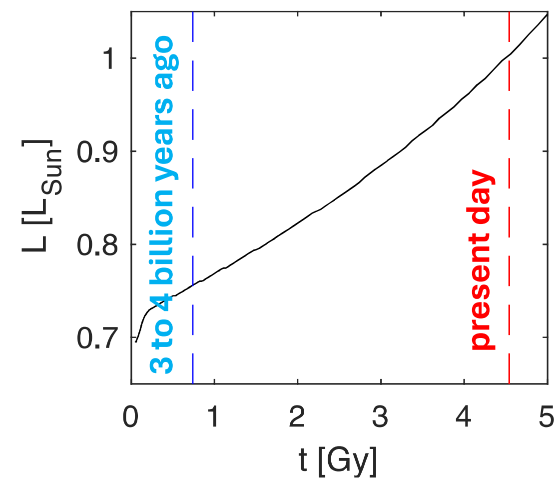


Ehlmann & Edwards 2014

The Faint Young Sun Paradox



Solar luminosity evolution
[data from Baraffe et al. 2015]

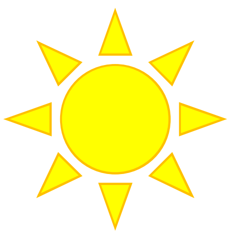


Equilibrium temperature calculation:

$$T_{eq} = \left(\frac{(1-A)}{\sigma} \frac{\alpha F_0}{4d^2} \right)^{1/4}$$

$$T_{eq,max} = \left(\frac{110 \text{ W/m}^2}{\sigma} \right)^{1/4} = 210 \text{ K}$$ **(-63 C)**

The Faint Young Sun Paradox



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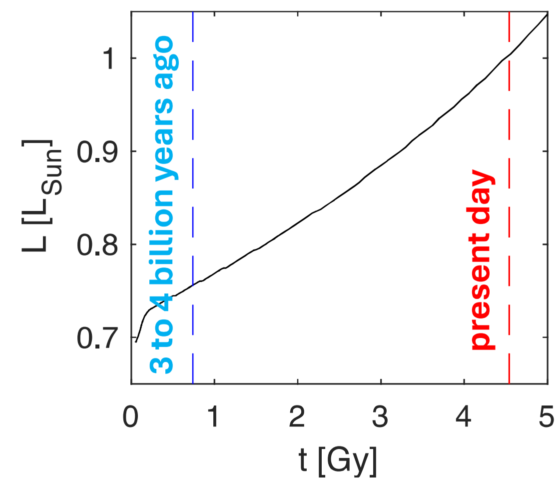

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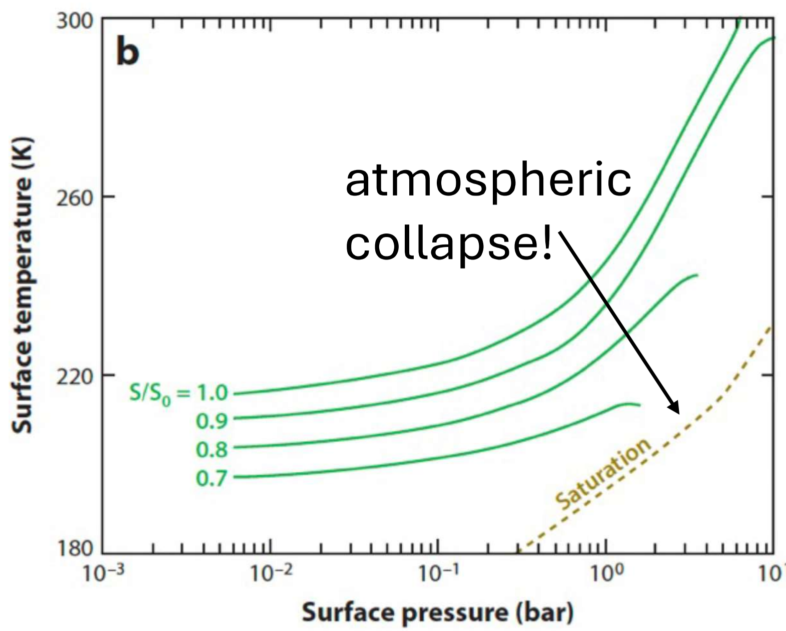
Possible Solutions

1. Orbital distance d was different early on
    - No – protoplanetary disk disperses too quickly after formation
2. Young Sun was more luminous (α was larger)
    - Possible if mass loss rate was very high, but conflicts with observations of nearby Sun-like stars
3. Surface temperature did not equal equilibrium temperature
    - **Requires a strong atmospheric greenhouse effect**

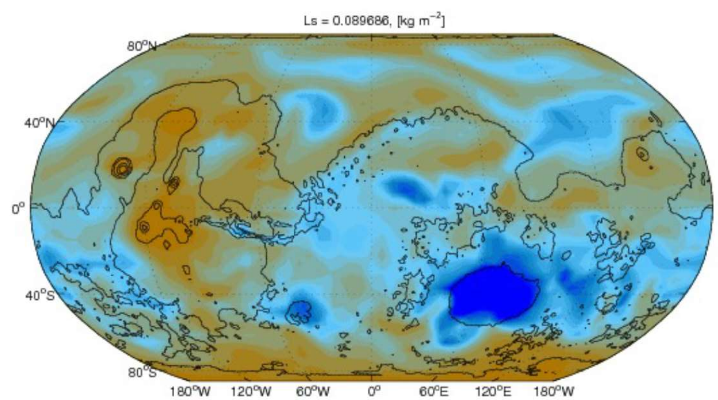
Dense CO_2 atmospheres do not warm enough



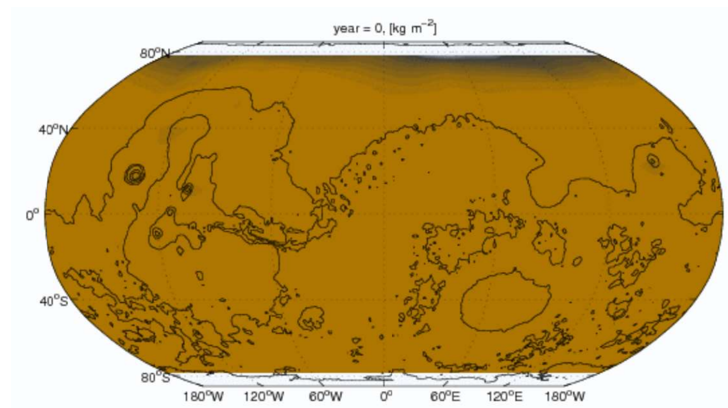
Wordsworth 2016 (from Kasting 1991)

3D modeling reveals how the early water cycle operated

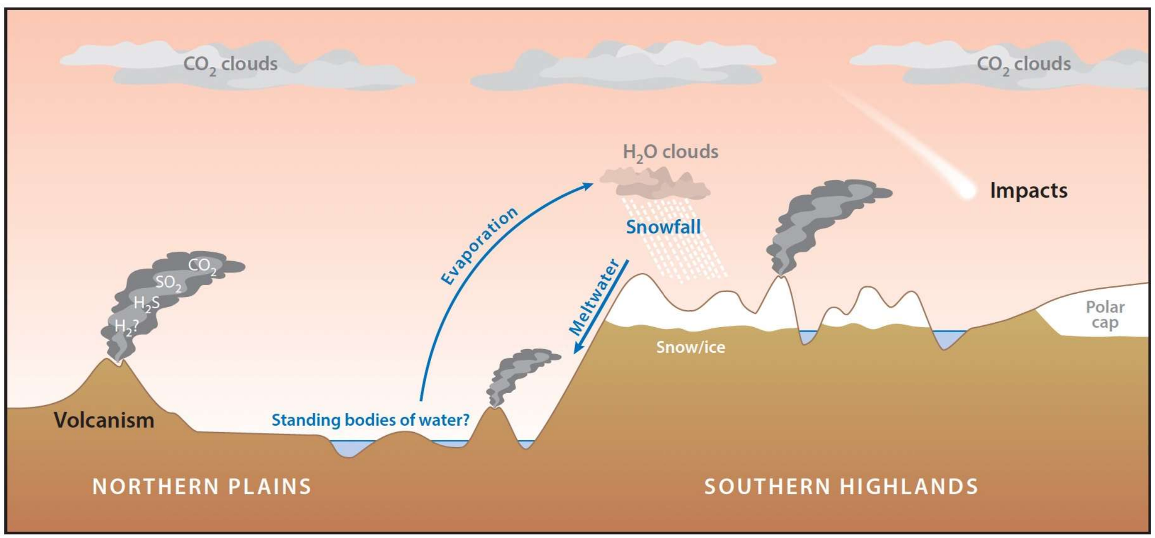
A few days of simulation time:

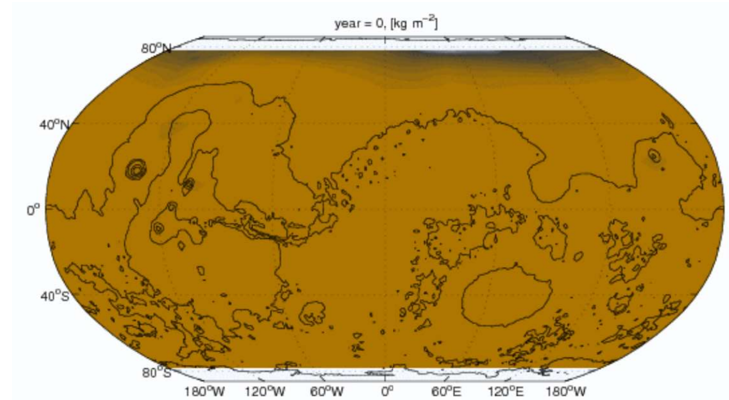


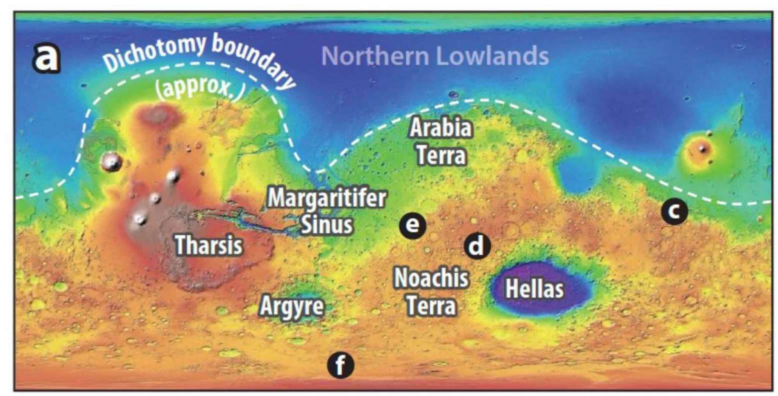
A few 1000 years of simulation time:



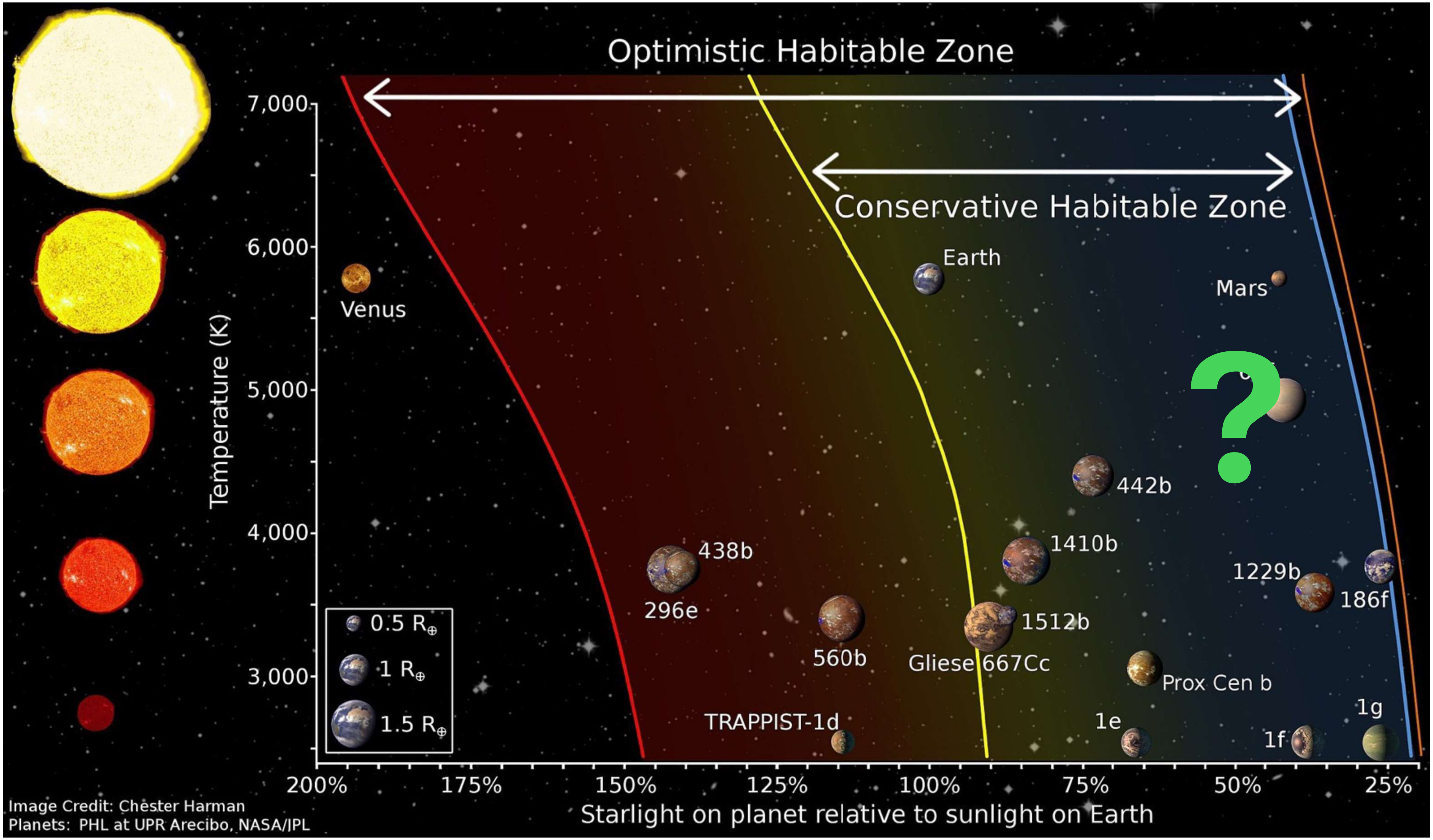
3D modeling reveals how the early water cycle operated



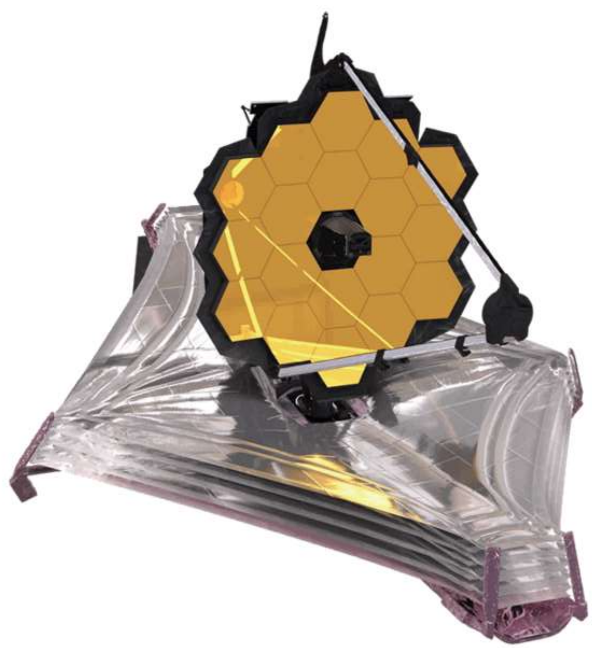


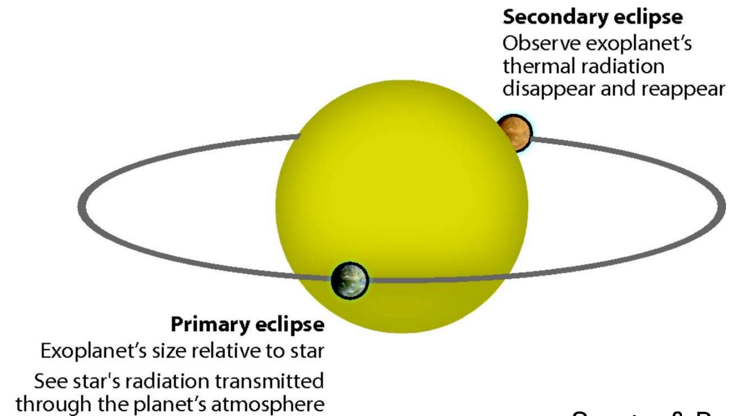


Wordsworth et al. 2013; Forget et al. 2013; Kerber et al. 2015, Wordsworth 2016; Palumbo et al. 2018; Kamada et al. 2020; Guzewich et al. 2021


Optimistic Habitable Zone
Conservative Habitable Zone
7,000
6,000
5,000
4,000
3,000
Temperature (K)
Venus
Earth
Mars
?
442b
438b
296e
1410b
1229b
186f
560b
1512b
Gliese 667Cc
Prox Cen b
TRAPPIST-1d
1e
1f
1g
0.5 R⊕
1 R⊕
1.5 R⊕
200%
175%
150%
125%
100%
75%
50%
25%
Starlight on planet relative to sunlight on Earth
Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL

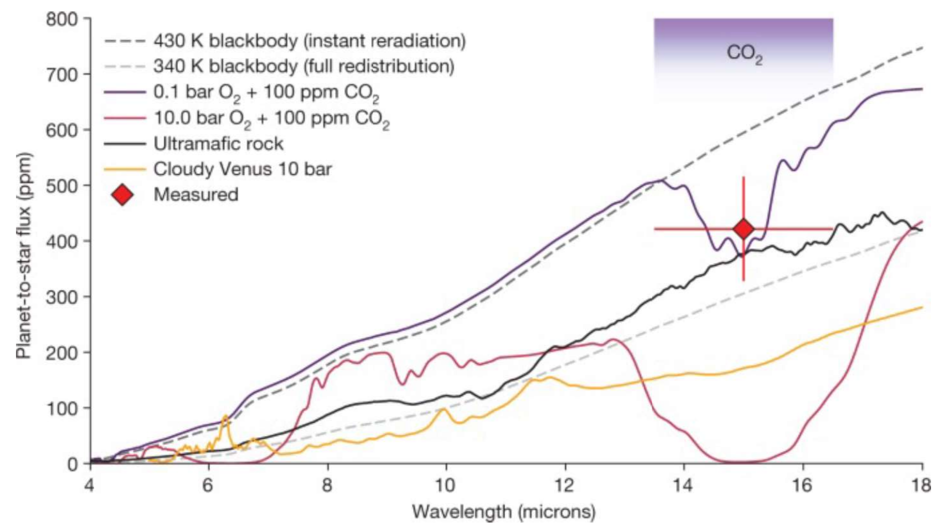
Mars-like rocky exoplanets





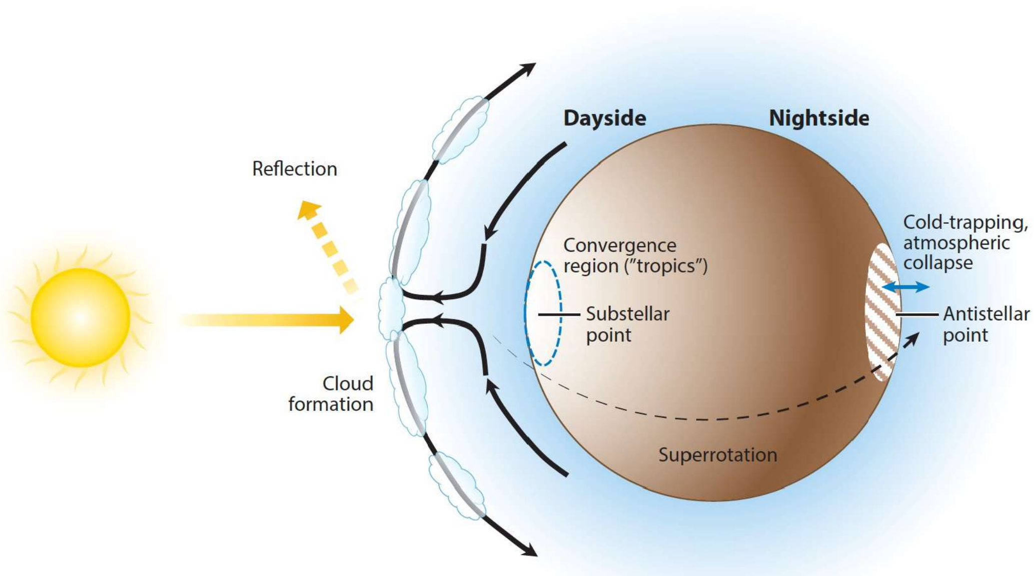
Seager & Bains, 2015

Dayside thermal emission of TRAPPIST-1c

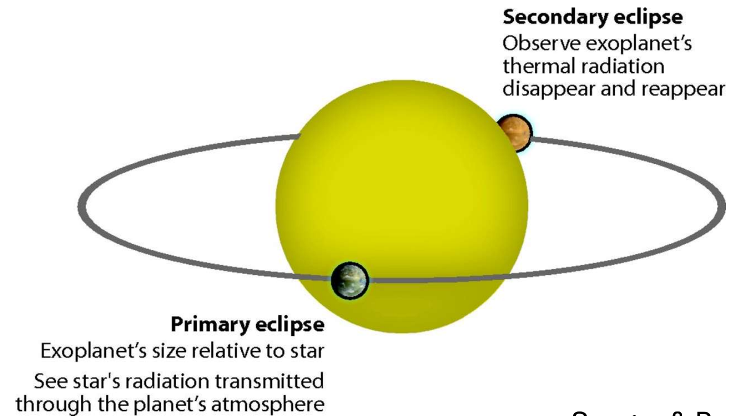


Zieba et al. 2023

Mars-like rocky exoplanets



Wordsworth & Kreidberg, 2022



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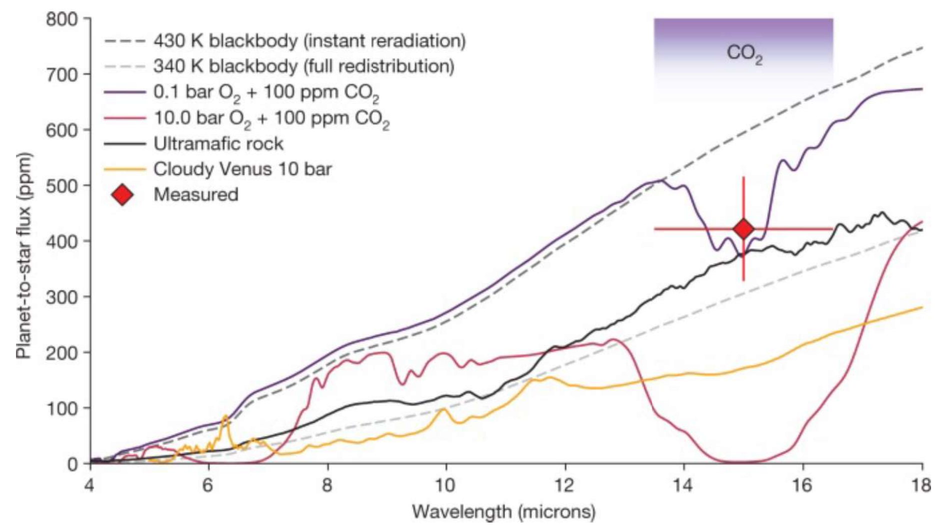
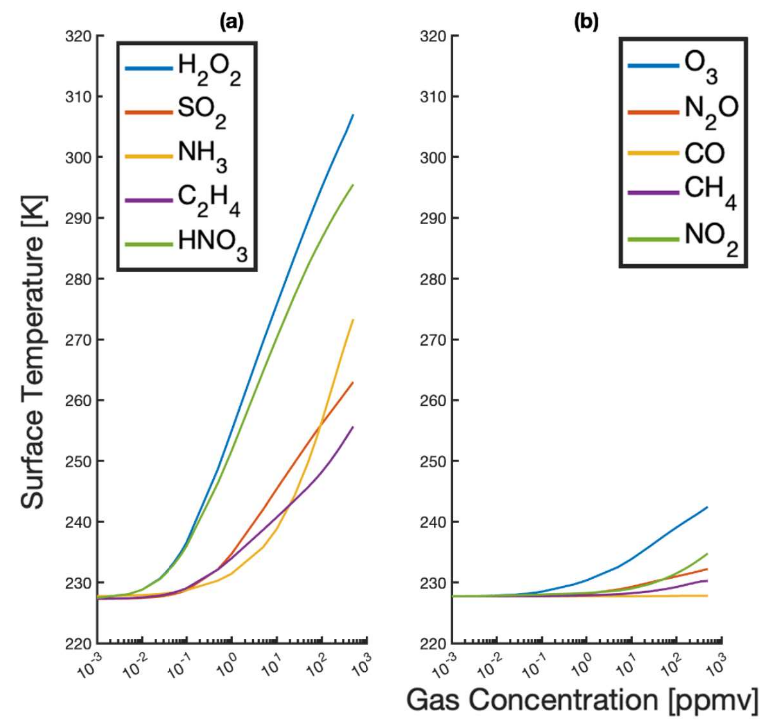


Zieba et al. 2023

Warming mechanisms

- Extended warm episodes (10^4-10^7 y) needed; permanently warm conditions are not
- Robust warming predicted in reducing CO_2-H_2 atmospheres (Ramirez et al. 2014, Wordsworth et al. 2017, others)
- Additional contribution from CO_2 ice clouds (Forget et al. 2013)
- Water ice cloud warming model-dependent but also a potential contributor (Wordsworth et al., 2013; Urata & Toon 2013; Kite et al. 2021; Steakley et al. 2023; Ding et al. 2024; Naar et al., this conf.)
- Other gases could also have contributed, depending on sources and sinks

Complete survey of HITRAN database!



Jorge & Wordsworth, *in revision*, 2024

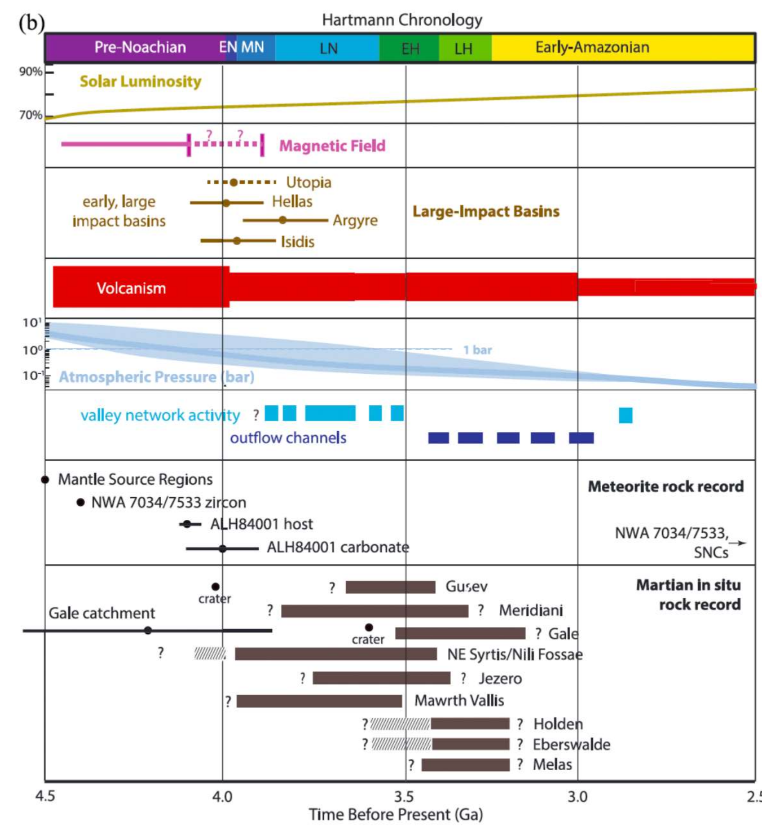
So, what new data is needed to make progress?

1. Quantitative estimates of *when* key events occurred
2. Constraints on surface temperature
3. Constraints on the water cycle
4. Constraints on atmospheric composition

1. Quantitative estimates of *when* key events occurred

Isotope Geochronology

- Which is the correct crater chronology?
- What was the solar flux when a lake was present at Jezero?
- When did the martian dynamo shut down?
- What was the time scale of aqueous processes at Jezero crater?

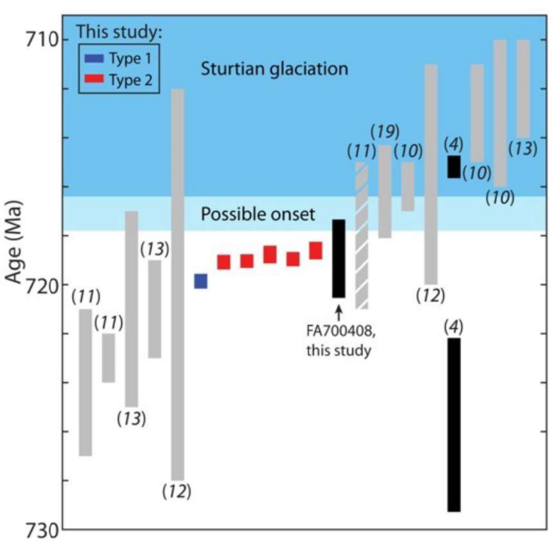


Ehlmann et al. 2016

1. Quantitative estimates of *when* key events occurred

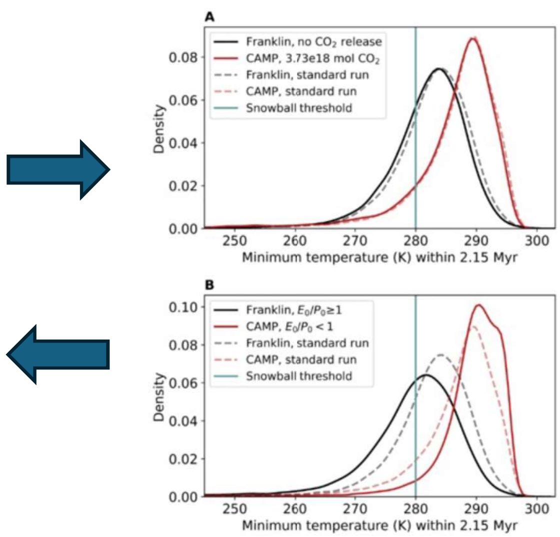
Contemporary Earth Science Example:
Neoproterozoic Snowball Earth Initiation

Geochronology



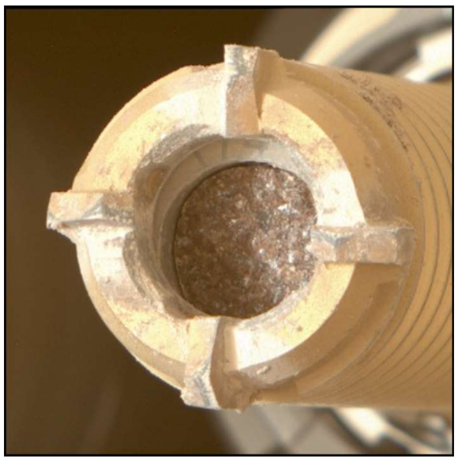
Pu et al. 2022

Snowball Initiation Modeling

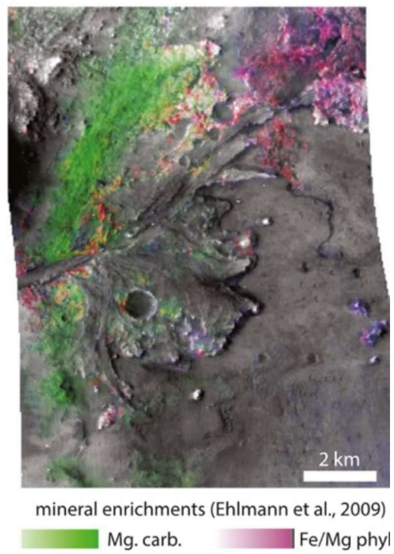


Minsky et al. 2024

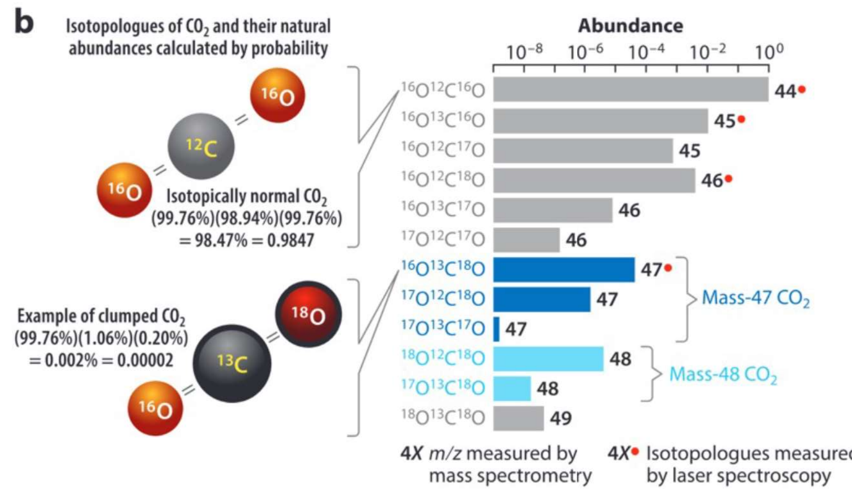
2. Constraints on surface temperature



https://science.nasa.gov/blogs/comet-geyser-perseverances-21st-rock-core/



Scheller et al. 2021



Huntington & Petersen 2023

PNAS

Carbonates in the Martian meteorite Allan Hills 84001 formed at 18 ± 4 °C in a near-surface aqueous environment

Itay Halevy[1,2], Woodward W. Fischer, and John M. Eiler

Geological and Planetary Sciences, California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125

Edited by Mark H. Thiemens, University of California San Diego, La Jolla, CA, and approved September 2, 2011 (received for review June 10, 2011)

Despite evidence for liquid water at the surface of Mars during the Noachian epoch, the temperature of early aqueous environments has been impossible to establish, raising questions of whether the surface of Mars was ever warmer than today. We address this problem by determining the precipitation temperature of secondary carbonate minerals preserved in the oldest known sample of Mars'

reported relative to the Pee Dee Belemnite standard) values of 25–35‰ (15–18). Their rims are Mg-rich, sometimes nearly pure $MgCO_3$, and have $\delta^{18}O_{SMOW}$ and $\delta^{13}C_{PDB}$ values as high as approximately 30‰ and 65‰, respectively. The veins and void fillings display covarying chemical and isotopic compositions similar to the concretions (12). The massive carbonates are usual-

3. Constraints on the water cycle

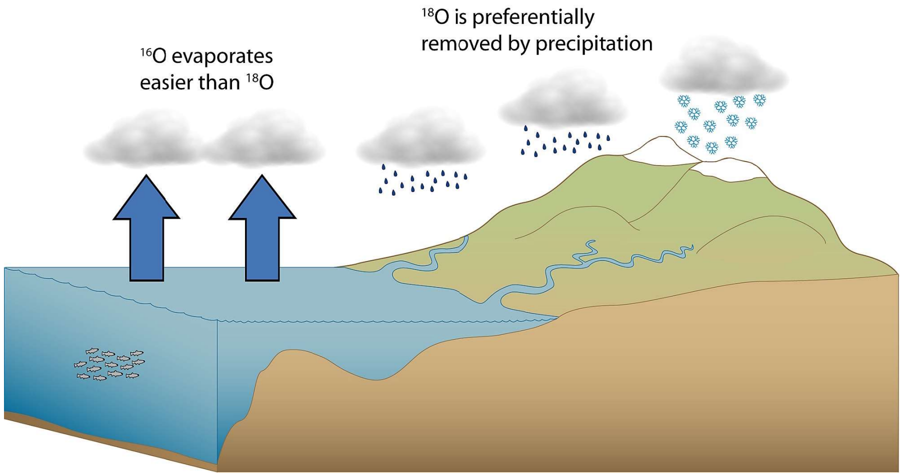
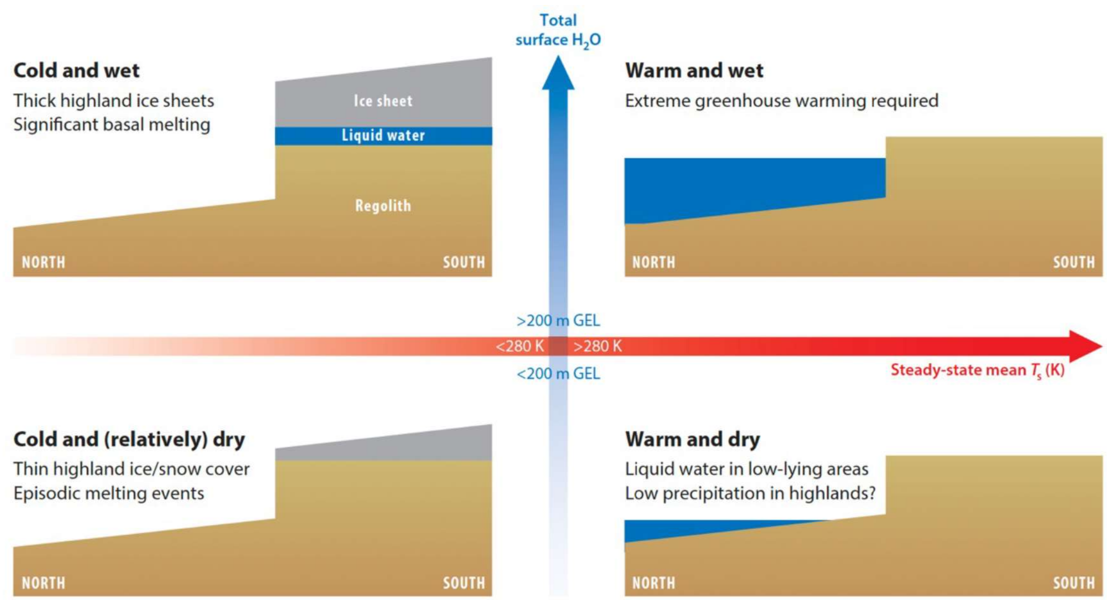


Image credit: Emma Versteegh



Wordsworth, 2016

But also:

- escape fractionation of O
- photochemical processes
- crustal interactions

E.g., Jakosky et al. 1994; Fox & Hać 2010; Alday et al. 2023

Requires further detailed study!

4. Constraints on atmospheric composition

a. How much CO_2 and N_2?
b. What was the atmospheric redox state?
c. What was the nature of the sulfur cycle?

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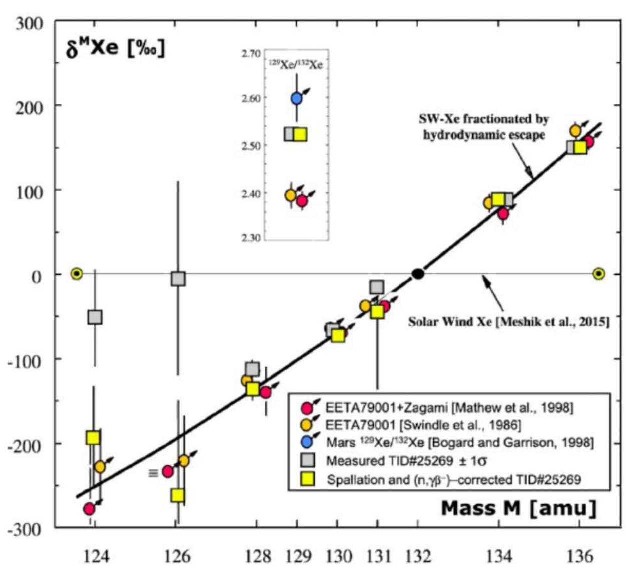


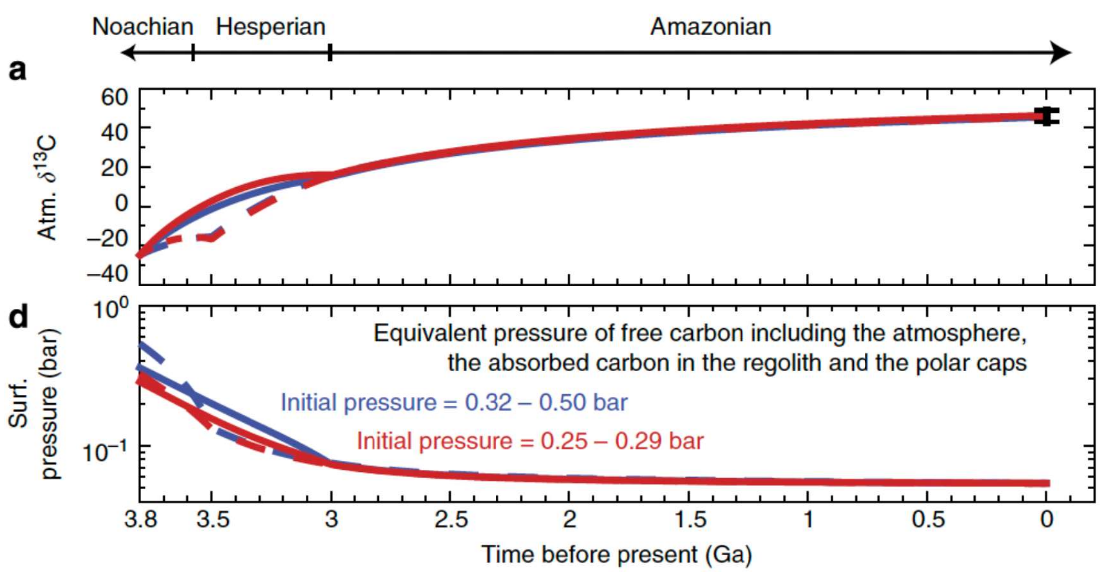
Scientific Value of Including an Atmospheric Sample as Part of Mars Sample Return (MSR)

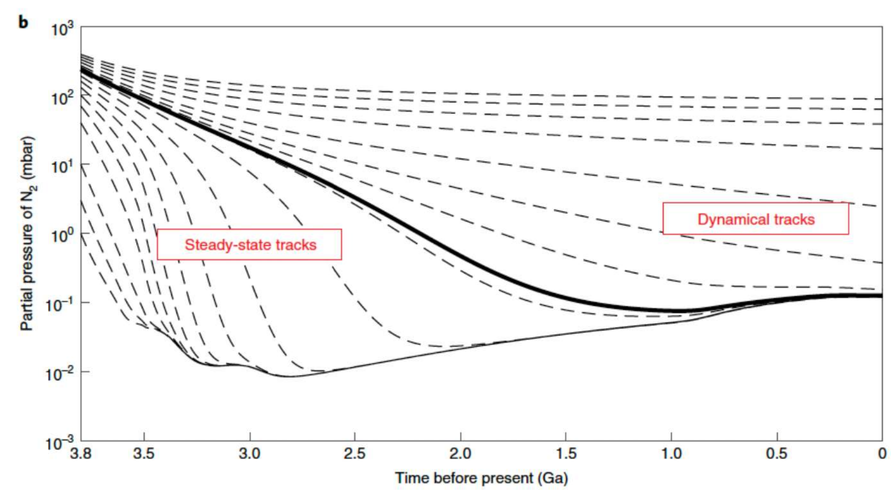
Timothy D. Swindle,[1] Sushil Atreya,[2] Henner Busemann,[3] Julia A. Cartwright,[4] Paul Mahaffy,[5] Bernard Marty,[6] Andreas Pack,[7] and Susanne P. Schwenzer[8]

The most exciting science can be obtained from a <u>compressed air</u> sample

4. Constraints on atmospheric composition

a. **How much CO_2 and N_2?**
b. What was the atmospheric redox state?
c. What was the nature of the sulfur cycle?





Hu et al., 2015; Hu & Thomas, 2023

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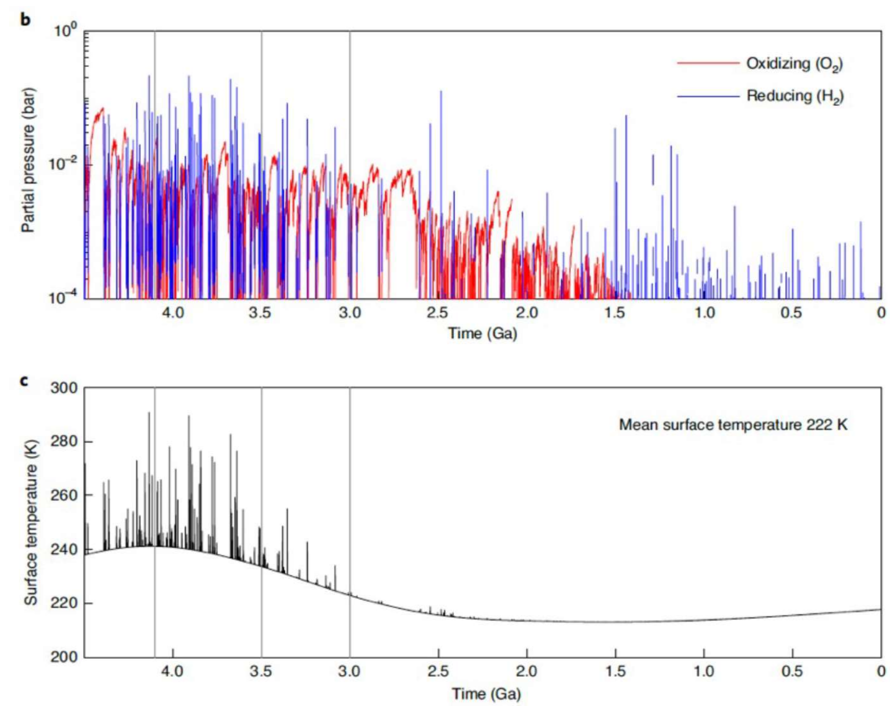
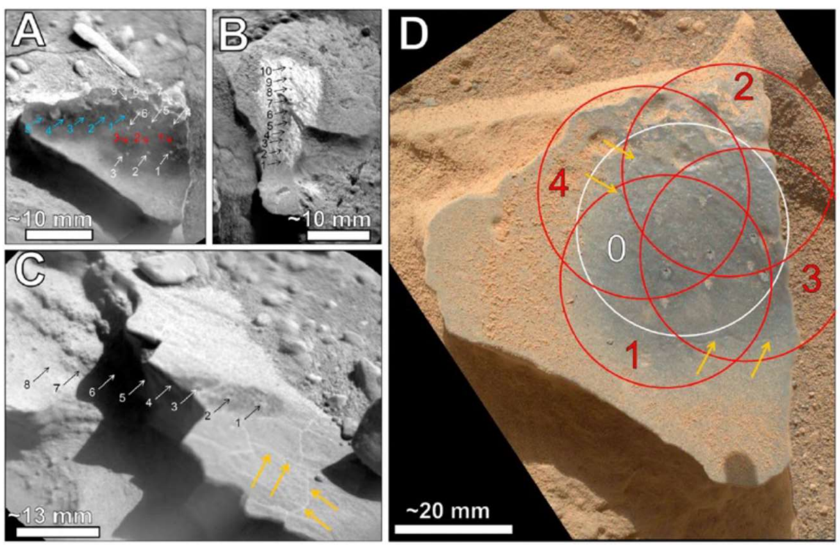


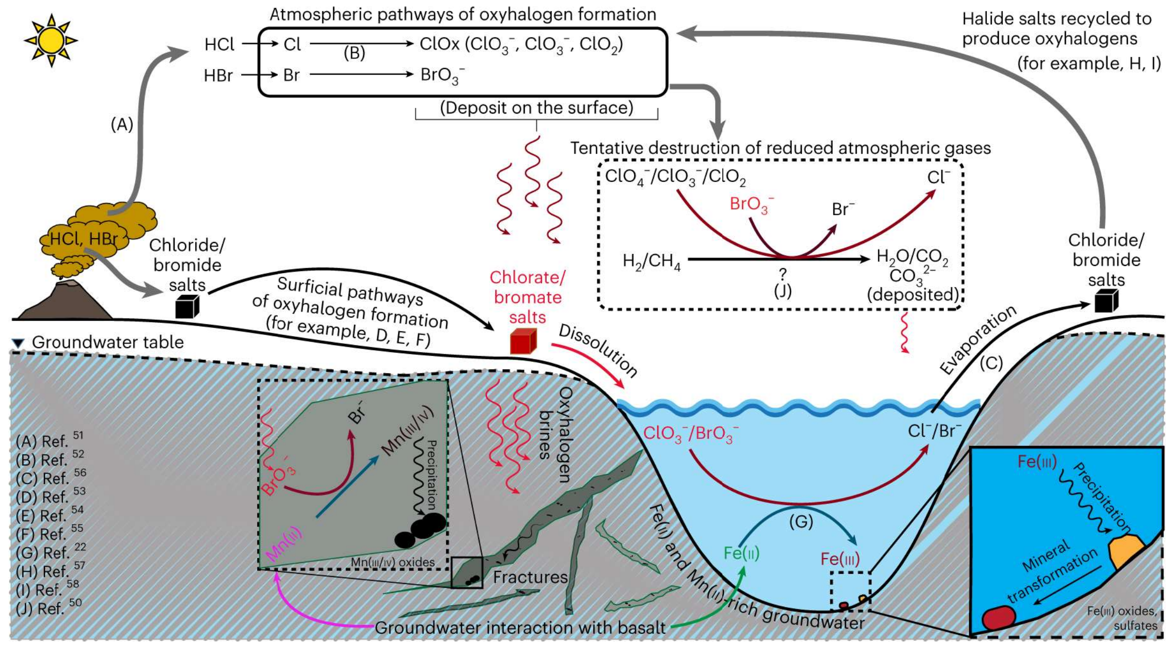
Wordsworth et al. 2021

4. Constraints on atmospheric composition

Manganese deposits imply elevated atmospheric O_2 (Lanza et al. 2016)



No! They can form from interaction with oxyhalide species (Mitra et al. 2023)



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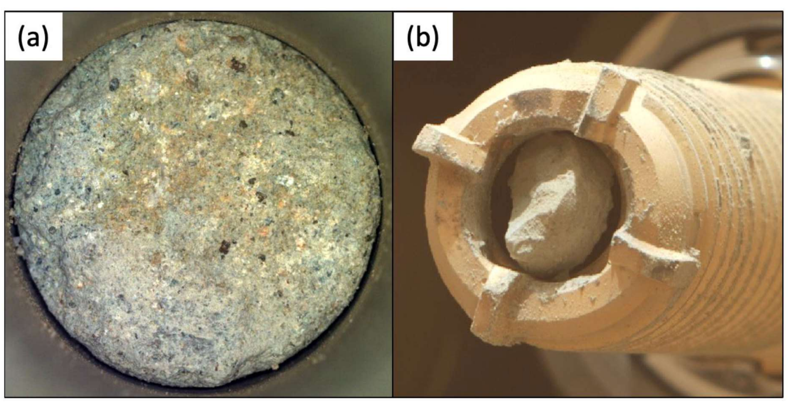
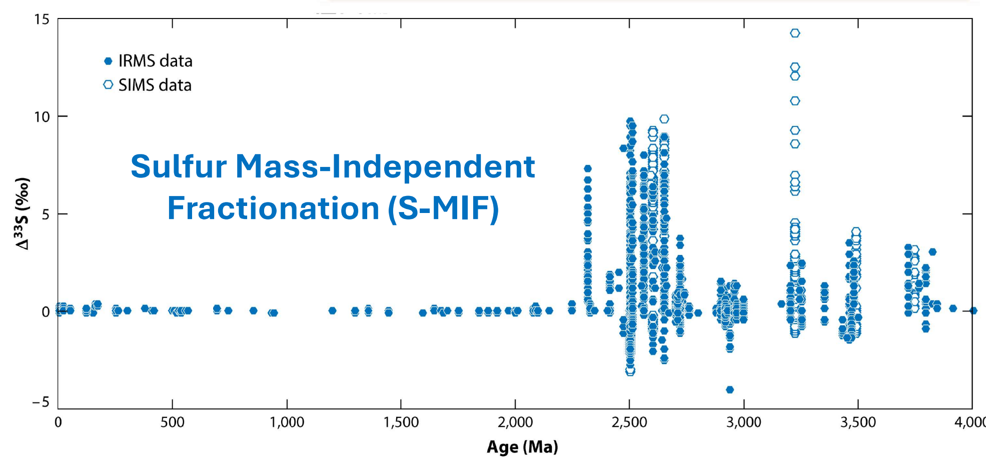
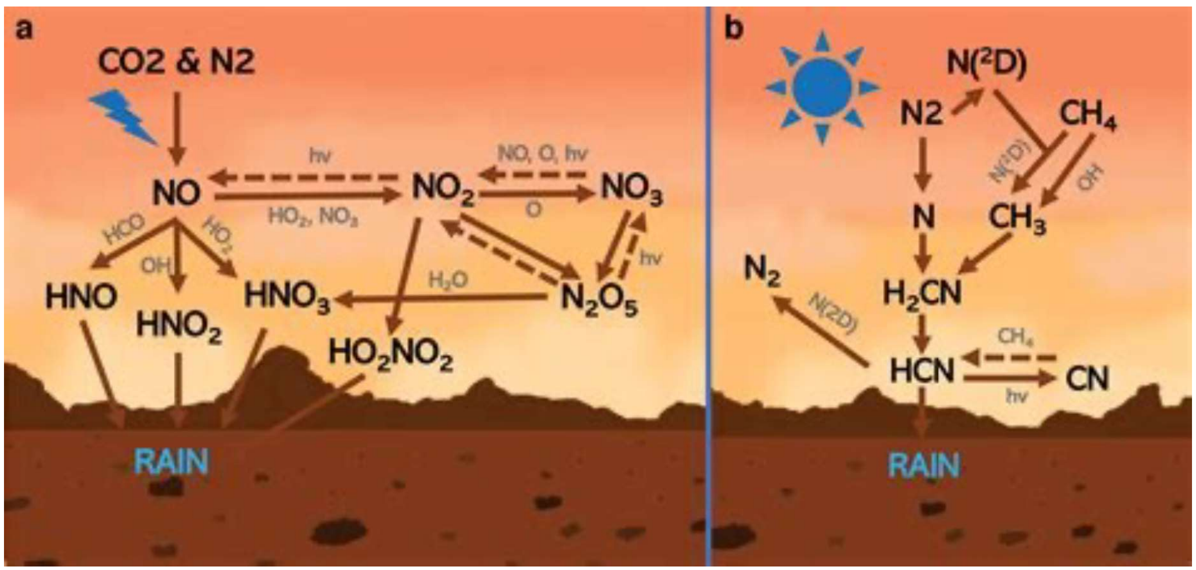


https://pds-geosciences.wustl.edu/m2020/urn-nasa-pds-mars2020_sample_dossier/initial_reports/initial_reports_volume2.pdf#page=151

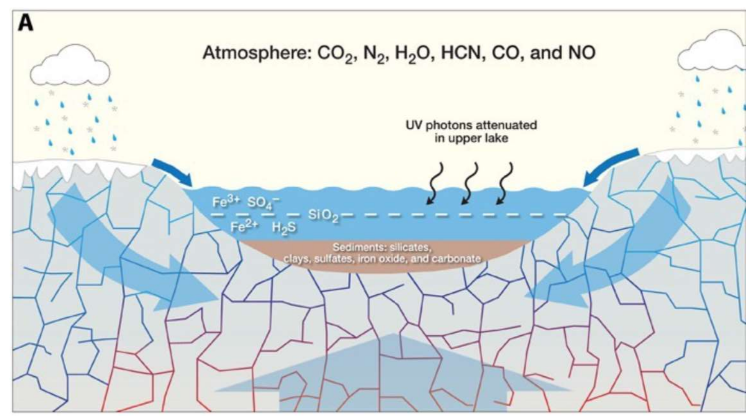


Ono et al. 2017

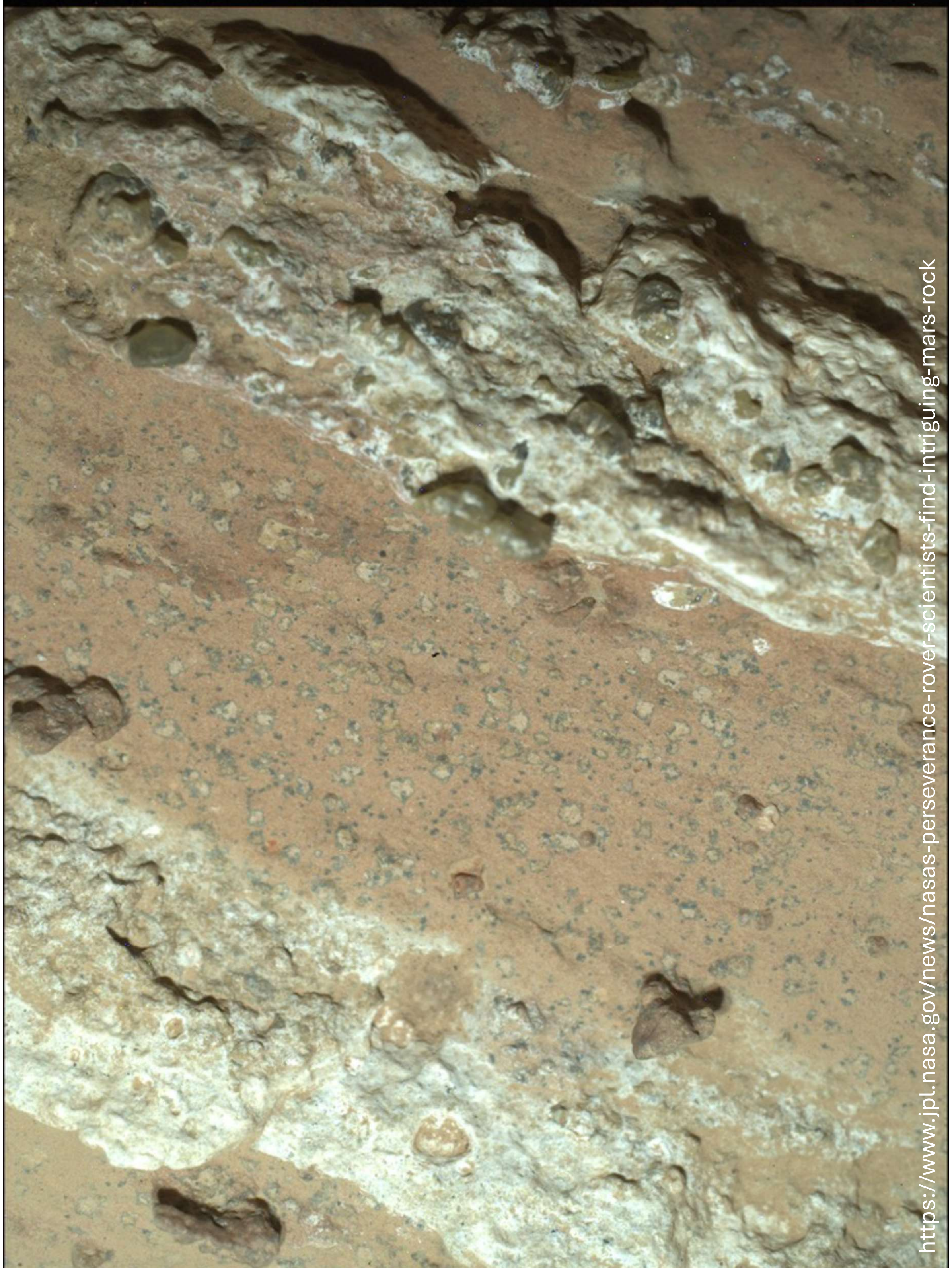
Atmospheric composition is vital context for prebiotic chemistry and biosignatures



Adams et al. 2021



Sasselov, Grotzinger & Sutherland, 2020



https://www.jpl.nasa.gov/news/nasas-perseverance-rover-scientists-find-intriguing-mars-rock

Issues specific to human exploration

- Field geology is probably the #1 area where humans have a decisive advantage over robotic platforms
- Modern field geology makes extensive use of drones. Humans on Mars will work best in close partnership with drones and other robots.

Most of the basis for these thoughts is the MHMSOTT report:
https://www.lpi.usra.edu/mepag/reports/reports/MHMSOTT-report-final.pdf

Issues specific to human exploration

- Key advantages:
  - Humans can rapidly contextualize information, iterate on discoveries and identify things that rovers will miss
  - Humans can carry out complex sampling and operate large instruments
  - Humans can triage samples for return to Earth and operate high-tech lab equipment at field bases
- Autonomy is *extremely important*: too-close supervision from Earth defeats the purpose of sending humans in the first place

Most of the basis for these thoughts is the MHMSOTT report:
https://www.lpi.usra.edu/mepag/reports/reports/MHMSOTT-report-final.pdf


I can’t see the rocks, they’re hidden by the Science Traceability Matrix on my visor!!
MARS EXPO
Pat Rawlings

Conclusions

- Mars is an archive of habitable conditions in the early solar system, at a time when life was first emerging on Earth
- The martian faint young Sun problem is one of the most important problems in planetary science, with implications for understanding the origin of life and exoplanet habitability
- Humans on Mars will enable huge advances on this problem