What makes a planet habitable?
Today

• Homework 5 is due now
• Homework 6 will be issued tomorrow and is due in class Tue 29 May
• People who have not yet done 2 presentations: identify yourselves for presenting Turbet et al. 2017 “The habitability of Proxima Centauri b: II – Possible climates and observability”
• Presentation of Ramirez & Kasting 2016
• Climate stabilization on Mars
Main drivers of atmospheric decline: escape-to-space (including impact erosion)

Lammer et al., Space Science Reviews, 2013
Evidence for water loss over time

- Current water reservoir
  - ~21 m (North + South PLD)

- Ancient water reservoir (4.5 Gyr)
  - ~137 m, 20% of surface

Possible water evolution based on atmospheric and meteoritic D/H measurements:

- Crust D/H - ALH84001
  - Boctor et al. 2003, Greenwood et al. 2008

- Clay minerals - Gale Crater
  - Mahaffy et al. 2015

- Mantle D/H - Yamato 980459
  - Usui et al. 2012

- Water D/H (VSMOW)
  - 8 (δD 7000 ‰)
  - 6 (δD 5000 ‰)
  - 1 (δD 0 ‰)

- Atmospheric D/H

- Polar water D/H

Atmospheric variability introduced by Vapor Pressure Isotope Effect (VPIE)

Villaneuva et al., Science 2015
Climate stabilization on early Mars

MODERN MARS CLIMATE

CARBON FEEDBACKS?

SULFUR FEEDBACKS?

HYDROGEN?

INTERMITTENCY?
The Case for a Wet, Warm Climate on Early Mars

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Fig. 1. (a) Surface temperature, $T_s$, and (b) planetary albedo, $A_p$, of Mars as the function of the surface pressure of CO$_2$ for the present surface albedo and globally and orbitally averaged solar flux. In (a), the solid curve presents results from this paper, while the other two curves represent results from two earlier calculations.
Fig. 2. Surface temperature as a function of surface pressure for several values of the surface albedo and incident solar flux, $S$. Solid lines refer to results for the current globally averaged albedo of 0.215. $S = 1$ for the present globally and orbitally averaged solar flux at Mars.
CO$_2$ condensation limits warming

Figure 12. Surface temperature as a function of surface pressure for four different values of the solar luminosity. Dashed line shows the saturation vapor pressure of CO$_2$. For the 0.7 and 0.8 luminosity cases, pressures greater than the maximum permitted would discontinuously move the curves down to the saturation vapor pressure [from Kasting, 1991].

Haberle,
JGR-Planets,
1998
Problem #1: where are the carbonates?

Carbonates are expected to form by water-rock reaction if pCO2 was high and pH was not acidic

Haberle, JGR-Planets, 1998
Fig. 2. Effects of atmospheric CO$_2$ and H$_2$O on global temperature. Error bars show mean and maximum/minimum surface temperature vs. pressure (sampled over one orbit and across the surface) for dry CO$_2$ atmospheres (red), and simulations with 100% relative humidity (blue) but no H$_2$O clouds. Dashed and dotted black lines show the condensation curve of CO$_2$ and the melting point of H$_2$O, respectively. For this plot simulations were performed at 0.2, 0.5, 1 and 2 bar; the dry and wet data are slightly separated for clarity only. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Problem #2: how much CO2 is enough?

Wordsworth et al. Icarus 2013
In addition to greenhouse warming, a thicker atmosphere is still useful for suppressing evaporitic cooling.

Assumes 273K surface & 200K atmosphere

Hecht 2002 Icarus
Climate stabilization on early Mars

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SO$_2$ inhibition of carbonate precipitation?

Bullock & Moore, GRL 2007
(contours = pH)

Halevy et al. Science 2007
SO\textsubscript{2}\textsuperscript{-}driven warming?

Halevy & Head, Nature Geoscience, 2014

Fluxes required to maintain these SO\textsubscript{2} concentrations, at steady state

Halevy & Head, Nature Geoscience, 2014
Figure 2 | Radiative forcing by $\text{SO}_2$ and $\text{H}_2\text{SO}_4$-coated dust. 

**a,** Global (dark and light blue) and subsolar zonal (red and orange) average outgoing radiation at the steady state, compared with the incoming solar flux (black and grey). 

**b,** Global and subsolar zonal average surface temperature at the same steady states as in **a,** and during a $\sim$30-year punctuated eruption (triangles, see Methods). Volcanic emission rates corresponding to the steady-state $\text{SO}_2$ mixing ratios on the horizontal axis are shown in the centre, along with estimated emission rate ranges of terrestrial and Martian volcanism. Numbered arrows show a possible positive feedback, described in the text.
Effect of Sulfur Gases on the Early Martian Atmosphere

Figure 1.

Even in the cases where large amounts of SO$_2$ and H$_2$S are added to the atmosphere, the annual global average surface temperature does not rise above freezing. H$_2$S provides significantly less warming than SO$_2$. 
Aerosol formation reduces SO$_2$ warming

Tian et al. EPSL 2010
Climate stabilization on early Mars

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H2 collision-induced absorption

Fig. 2 Evolutionary tracks for the time dependence of surface temperature for Mars for three early compositions and two different bolometric Russell–Bond albedos.

Climate stabilization on early Mars

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Olivine places an upper limit of $10^7 \text{ yr}$ of water over most of the surface

- Refers to soil-water contact (ice can shield soil from water)
- Physical erosion can ‘reset’ the surface

Koeppen & Hamilton, JGR-Planets, 2008
Paleolake hydrology requires $>10^{4-5}$ continuous wet years (e.g., seasonal runoff)
Statistics of intermittent habitability on Mars

Ongoing work
(Kite et al. LPSC 2015; Mansfield et al. JGR 2018.)
Mars terraforming: very difficult at best

Bad news: No credible source for breathable levels of O2
Good news: ~1 bar CO2 would be sufficient to warm surface for modern solar luminosity
Bad news: The CO2 may have all (or mostly) escaped to space
(Ehlmann & Edwards, Geology, 2014)
Good news: CFCs or SF6 can provide very strong warming
(Marinova et al., JGR-Planets, 2005)
Bad news: CFC/SF6 warming would probably not trigger runaway atmospheric re-inflation
(Bierson et al. GRL 2016)
Good news: ...

Common assumptions in the literature:
Initiate with relatively near-term (21st-century) technologies
Goal: Habitable for photosynthetic algae/plants
Asteroid kinetic energy, nuclear bombs, e.t.c. is insufficient

Mars terraforming: gases vs. particles

**Gases option:** Make on surface: Marinova+ 2005 JGR

**Particles option:** inject resonant absorbers at stratospheric height

**Deliver via impacts:**

Double Asteroid Redirection Test (launch 2020)

See also Teller et al., Lawrence Livermore National Lab report UCRL-231636/UCRL JC 128715
Key points: Mars

• Current Mars T, P, and magnitude of present day annual cycles of H$_2$O, CO$_2$, and dust;
• reasons in favor of, and problems with, the CO$_2$, SO$_2$, and H$_2$ solutions to the Early Mars Climate Problem;
• significance of the olivine and paleolake-hydrology constraints on Early Mars climate.