What makes a planet habitable?

Lecture 15
Mars
Tuesday 25 February 2020
Is Earth a fluke, or are habitable climates common?

Next steps:

- Present-day habitable planets: one example.
- Rock records of Earth and Mars: provide access to planetary systems operating differently from present-day planets.
Fig. 3  History of Mars’ river-forming climates (modified after Kite et al. 2017b). Y-axis corresponds to the map-view scale of the landforms shown. Neither the durations of geologic eras, nor the durations of river-forming climates, are to scale. Data are consistent with long globally-dry intervals. Dynamo timing is from Lillis et al. (2013). H = Hellas impact event. * = subsurface aqueous alteration as recorded by Mars meteorites (Borg and Drake 2005; Nemchin et al. 2014)
Main drivers of atmospheric decline: escape-to-space (including impact erosion)

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

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.
**CO₂ 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 CO₂. 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].
Problem #1: where are the carbonates?

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

Figure 13. Candidate reservoirs for an early CO2 atmosphere.

Haberle, JGR-Planets, 1998

Comanche: 16-34 wt% carbonate (Morris et al., 2010): but such outcrops are rare

Adding up known carbonate reservoirs yields << 1 bar CO2 equivalent
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$_2$-driven warming?

Fluxes required to maintain these SO$_2$ concentrations, at steady state

Halevy & Head, Nature Geoscience, 2014
Figure 2 | Radiative forcing by SO$_2$ and H$_2$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$30-year punctuated eruption (triangles, see Methods). Volcanic emission rates corresponding to the steady-state SO$_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.
**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$_2$. 

Kerber et al.  
JGR-Planets  
2015
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.

Weathering reactions make hydrogen

**Fig. 3 | Groundwater-lake water mixing to form magnetite and H\(_2\)(aq).**

a. Schematic of domain used in reactive transport simulations. b. Mineral volume fraction and H\(_2\)(aq) concentrations in coexisting solutions plotted as a function of olivine reaction progress. Note that H\(_2\)(aq) concentrations plotted here exceed the solubility of H\(_2\)(aq) in ambient-pressure solutions, and would be expected to generate a free gas phase within the sediments. The curvature in H\(_2\)(aq) is related to the diminishing reactivity of olivine as its volume fraction is depleted, and the increased diffusional gradient of H\(_2\)(aq) out of the domain.
Cloud warming?
The H$_2$O-ice cloud greenhouse for Early Mars$^1$ has proven difficult to replicate$^2$, and has been argued to require unrealistic cloud lifetimes and unrealistic cloud coverage.$^{3,4}$

**Warming** if clouds are high & ice grain $r \geq 5\mu m$

**Cooling** if clouds are low

Warm climates emerge in our simulations.
Annual average temperature > 290K on Mars highlands.

Cold/dry start. Contours mark elevation in m. Letters are current (C,S,O) and future (NASA, ESA) rover sites.
Climate stabilization on early Mars

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Olivine places an upper limit of $10^7$ 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)

Irwin et al., Geomorphology 2015
Statistics of intermittent habitability on Mars

Ongoing work
(Kite et al. LPSC 2015; Mansfield et al. JGR 2018.)
Can Mars be made habitable in the near future? 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


Falcon Heavy: 17 tons to Mars
Can Mars be made habitable in the near future? 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.
Backup/additional slides