Early Life Crises of Habitable Worlds

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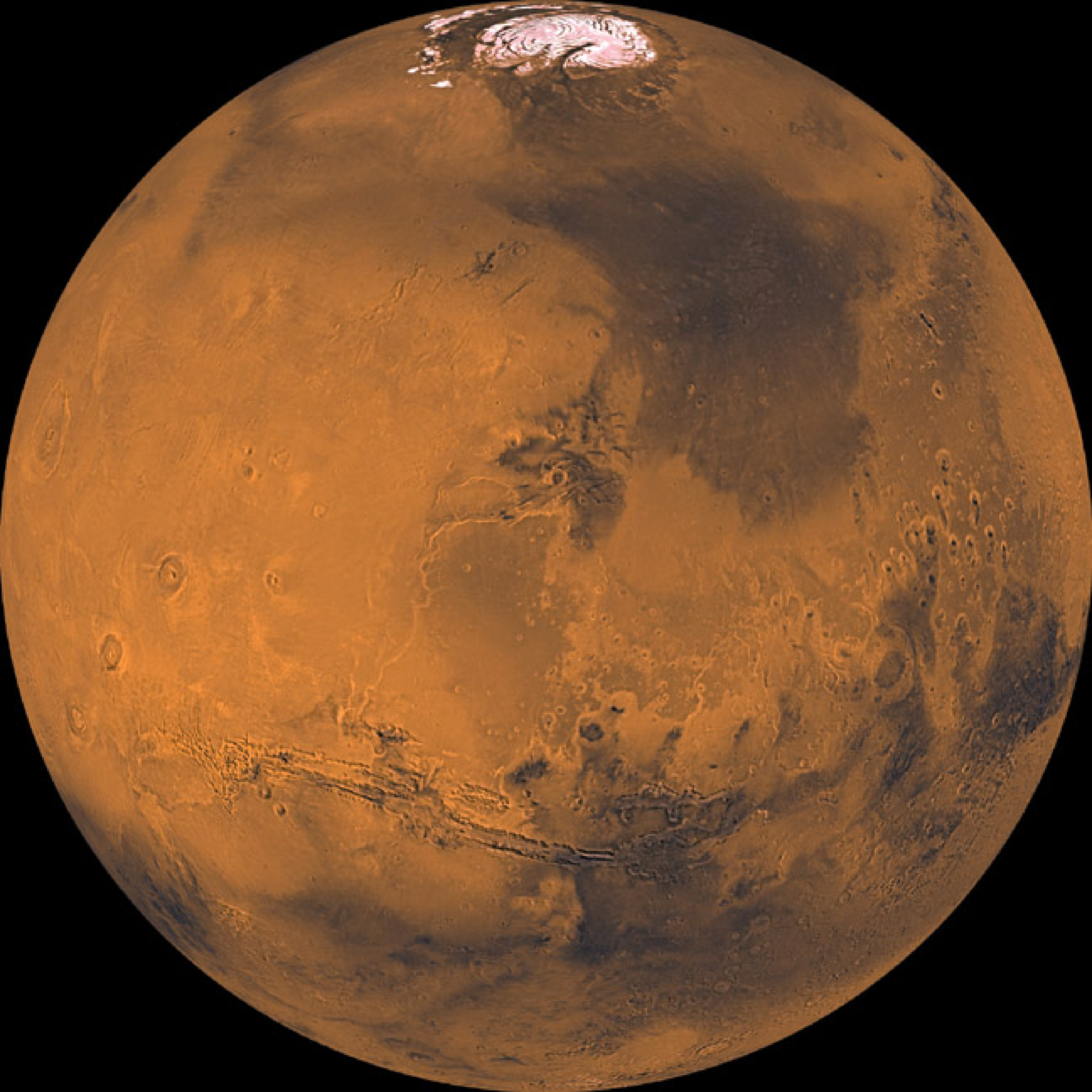
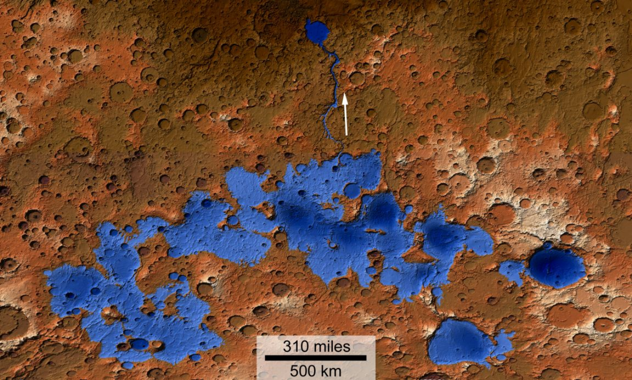
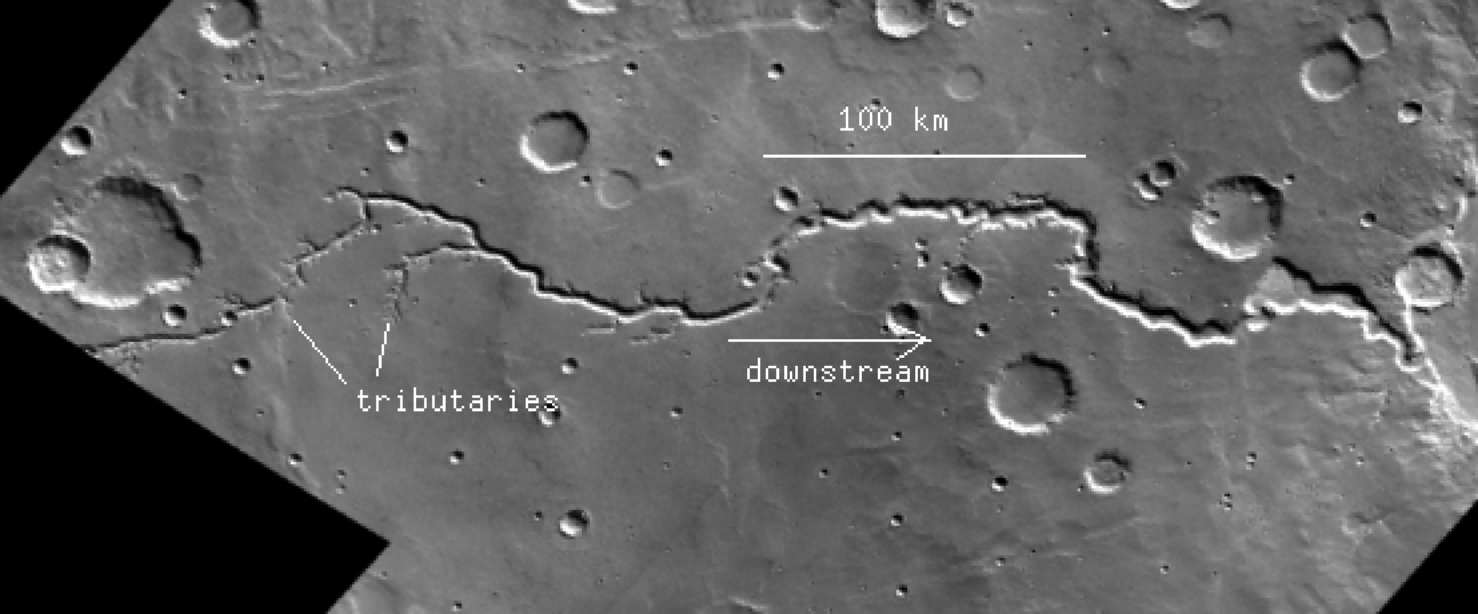
The essential problem

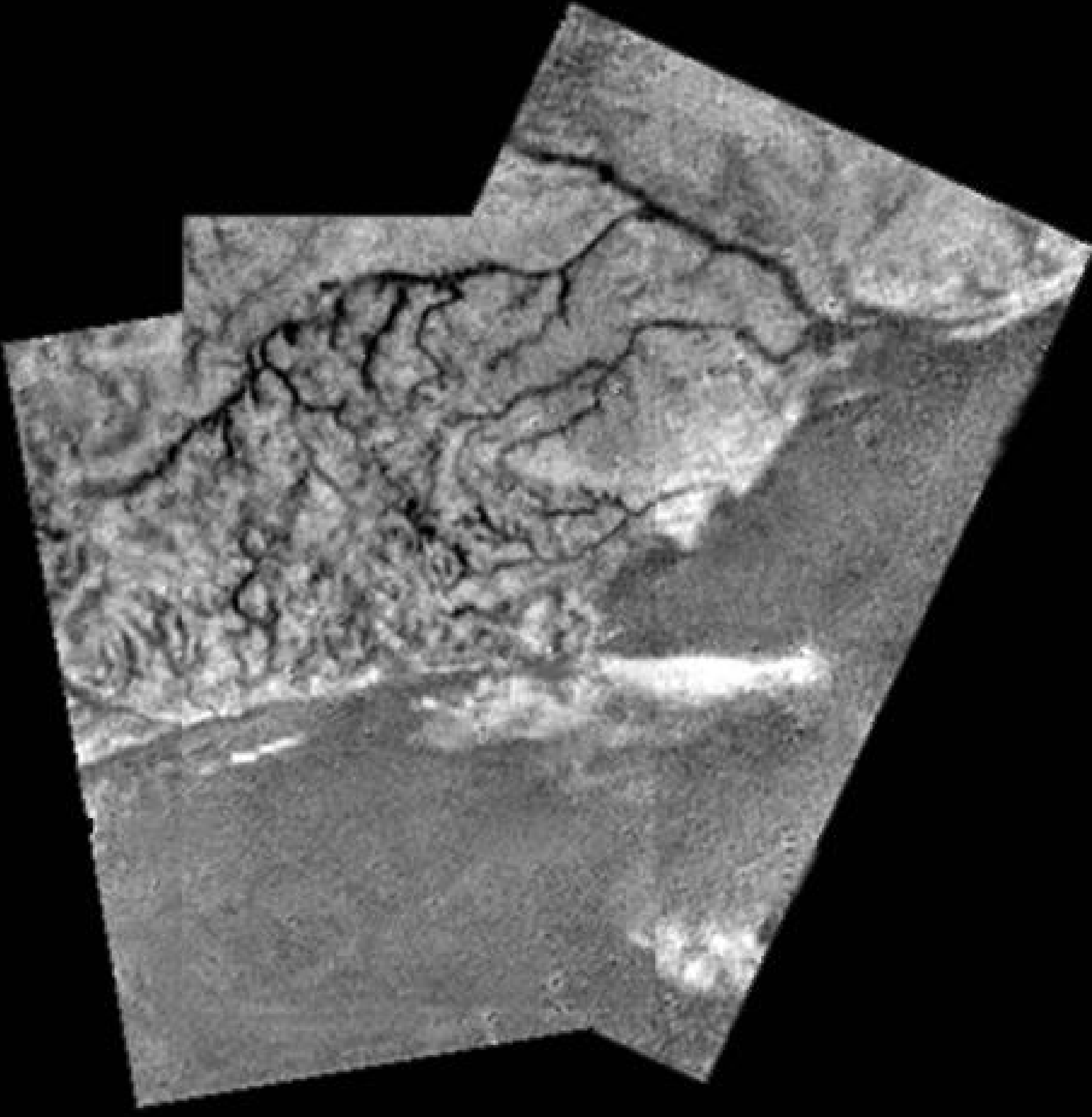
How to keep climate stable over billions of years against:

- Continual increase in brightness of the star
- Evolution of the atmosphere due to chemical and physical processes




310 miles
500 km


100 km
downstream
tributaries



No time to waste!

Life arose very quickly on Earth but

- It took 3 billion years for multicellular life to appear
- Intelligent life has been around for only 500,000 years or so
- There might be under a billion years left in the life of the biosphere

The Clausius-Clapeyron Rule

In equilibrium with a volatile reservoir, the atmospheric pressure is

$$p_s(T) = ae^{-T^*/T}$$

eg for N_2:

- 70K supports a 350 mb atmosphere
- 100K supports a 6 bar atmosphere
- 150K supports a 56 bar atmosphere

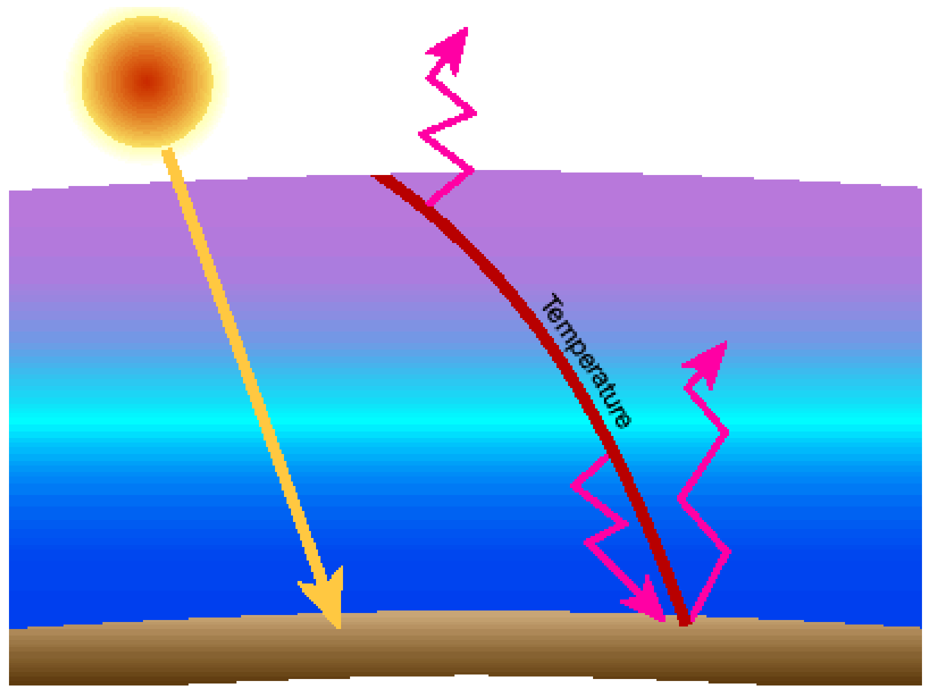
and for CH_4:

- 70K supports a 5mb atmosphere;
- 100K supports a 300 mb atmosphere;
- 150K supports a 8.5 bar atmosphere

What if the gas affects the temperature of the planet?

Radiation budget, blackbody radiation and the Greenhouse effect

$(1-\alpha)S = \sigma T^4$, but which T?

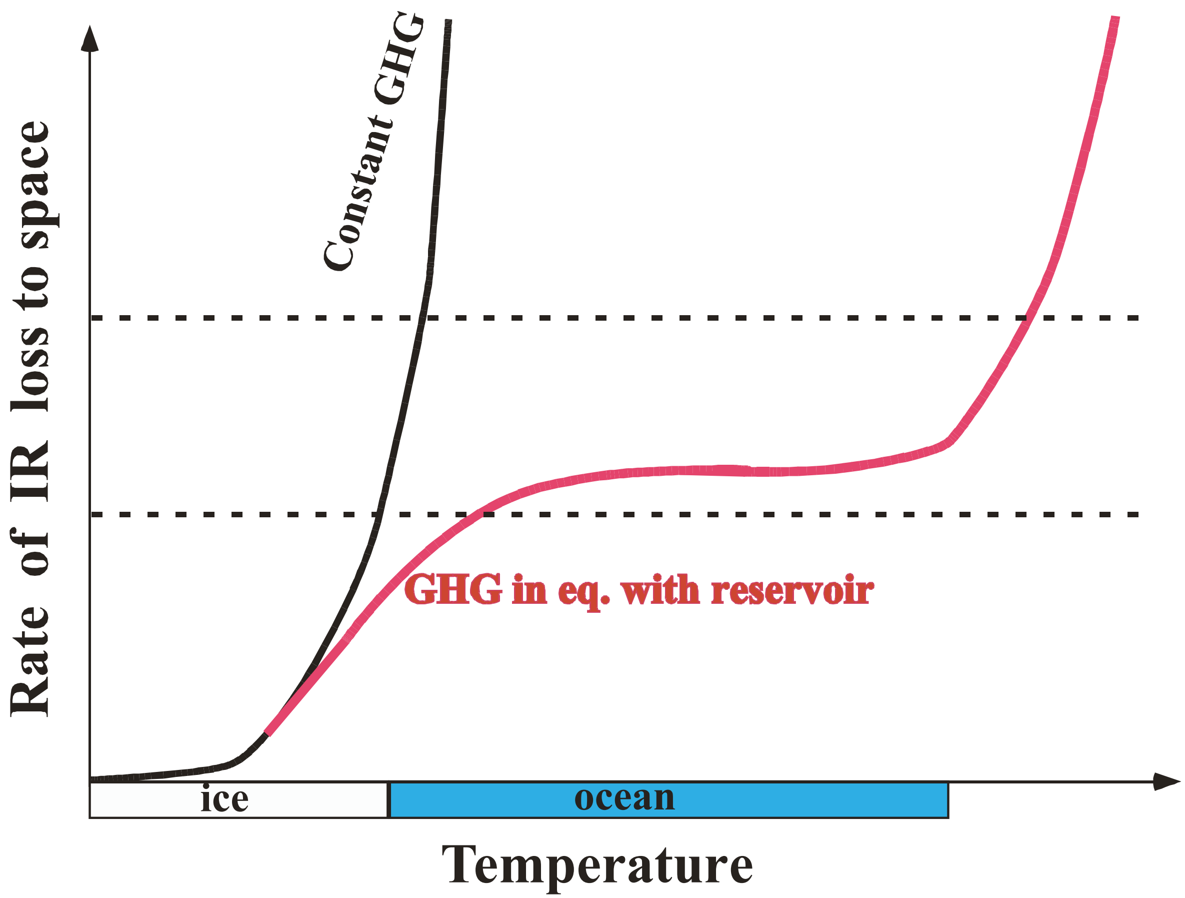


Note: $M = p_s/g$

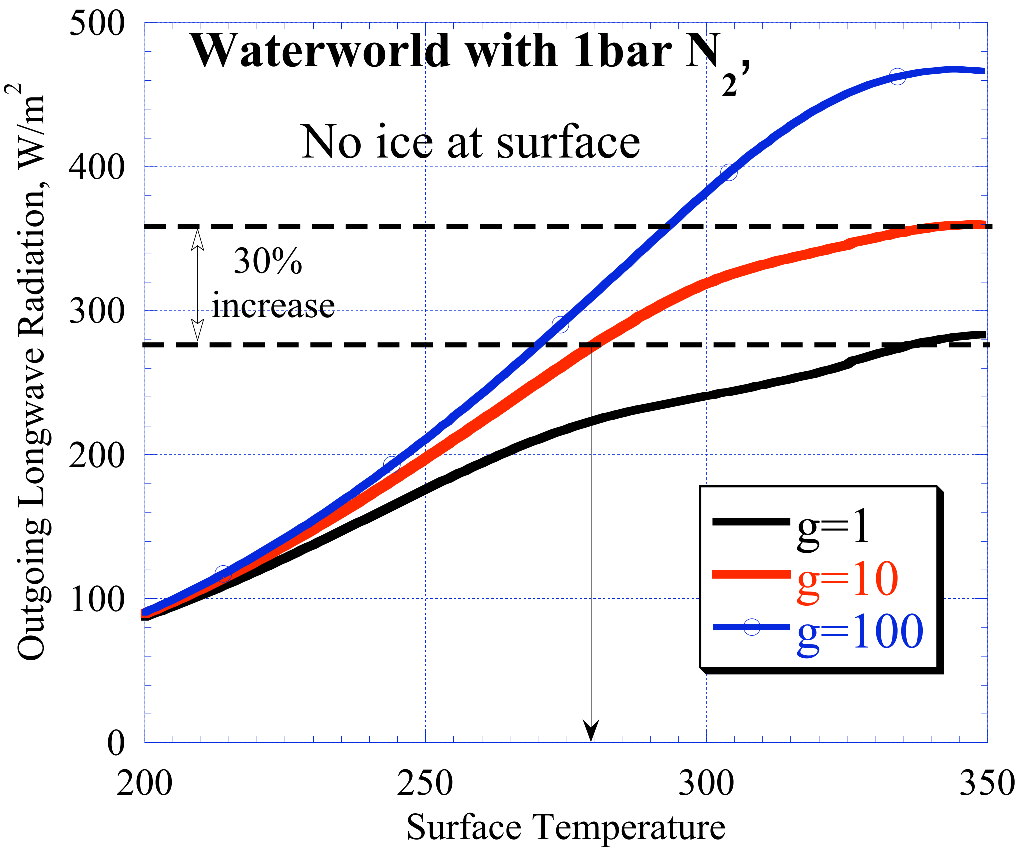
A word about σ

$$\sigma = \frac{2\pi^5}{15}\frac{k^4}{c^2 h^3}$$

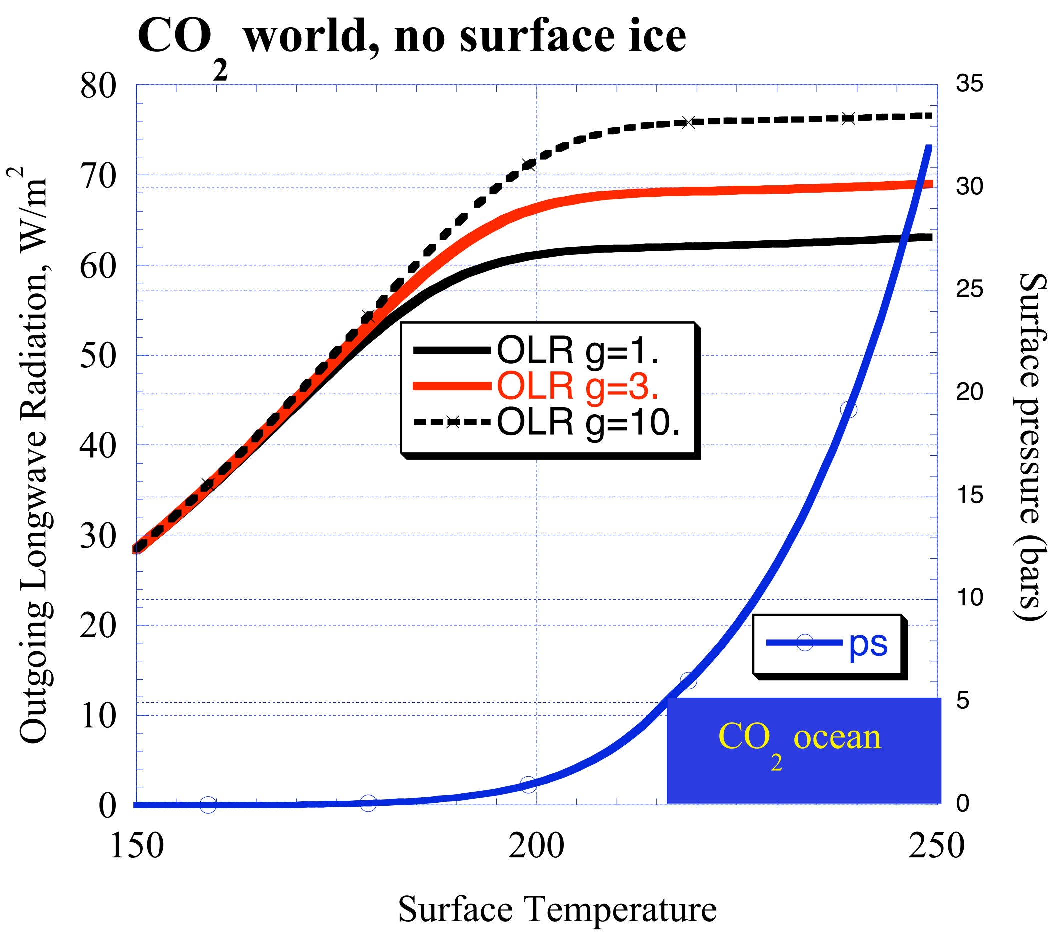
The Clausius-Greenhouse Feedback



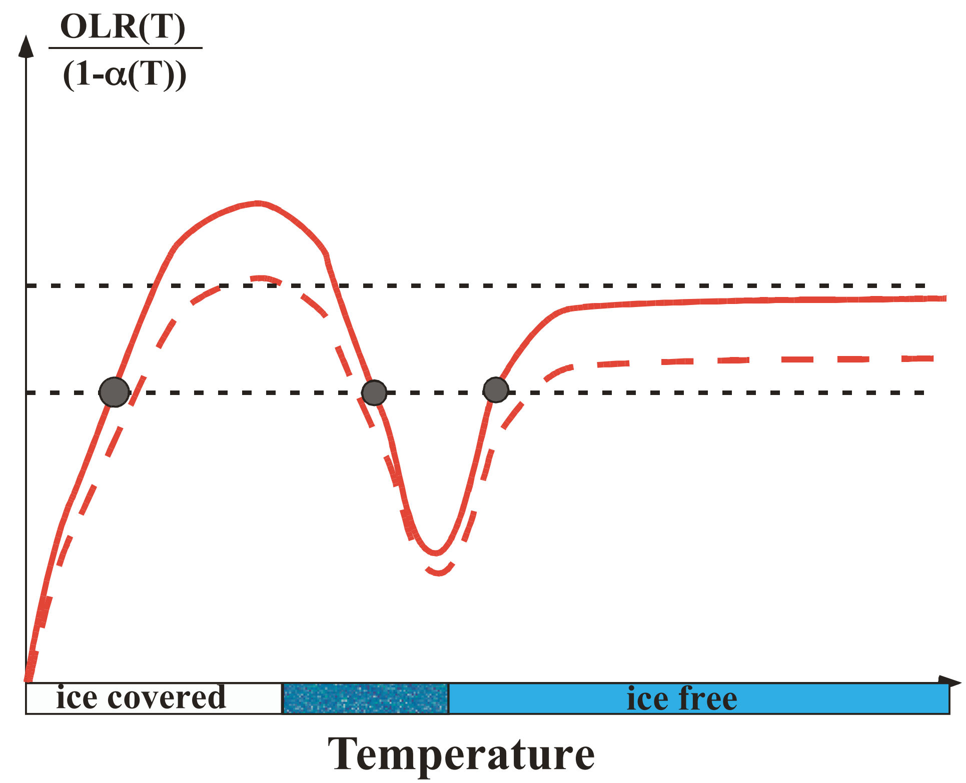
A water-world



A water-world

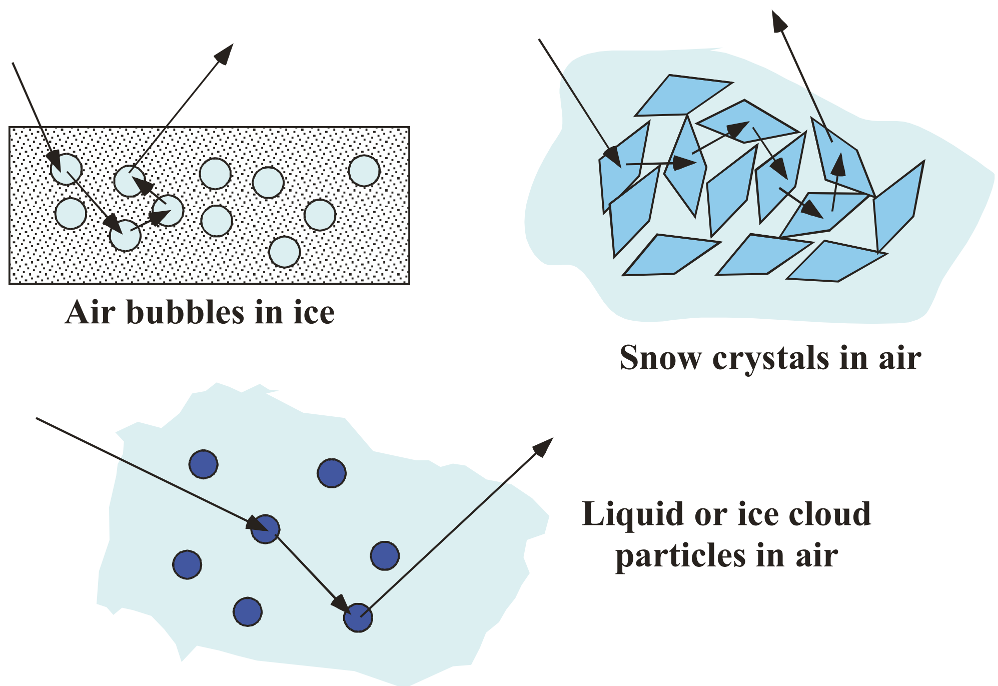


The ice-albedo bifurcation diagram $(1-\alpha(T))S = OLR(T,\lambda)$



How transparent stuff becomes reflective

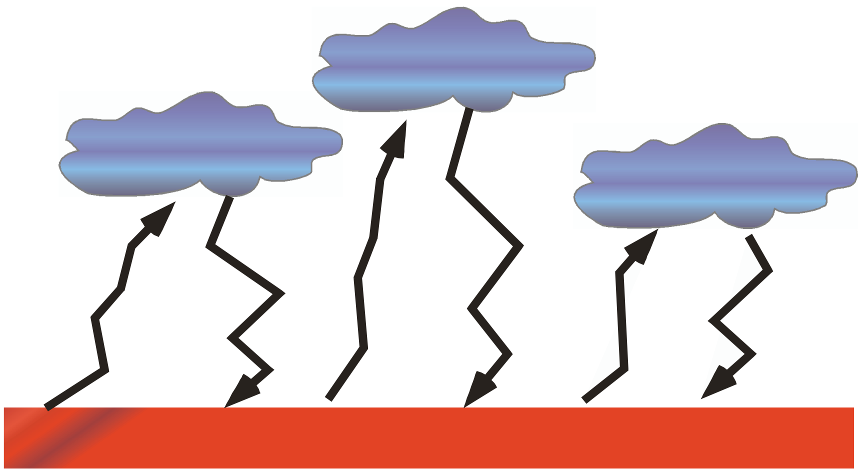
Index of refraction discontinuities lead to scattering



CO_2 clouds reflect infrared

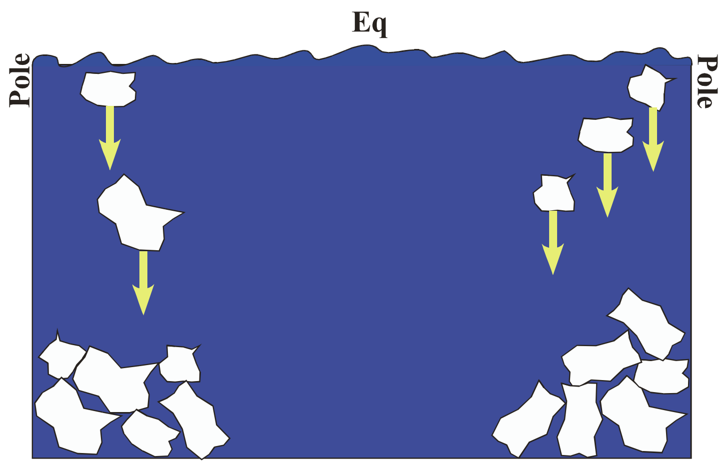
Forget and Pierrehumbert, *Science*, 1996.

This warms the surface, and can possibly bring Early Mars into the habitable zone with about 2 bars of CO_2 in the atmosphere.



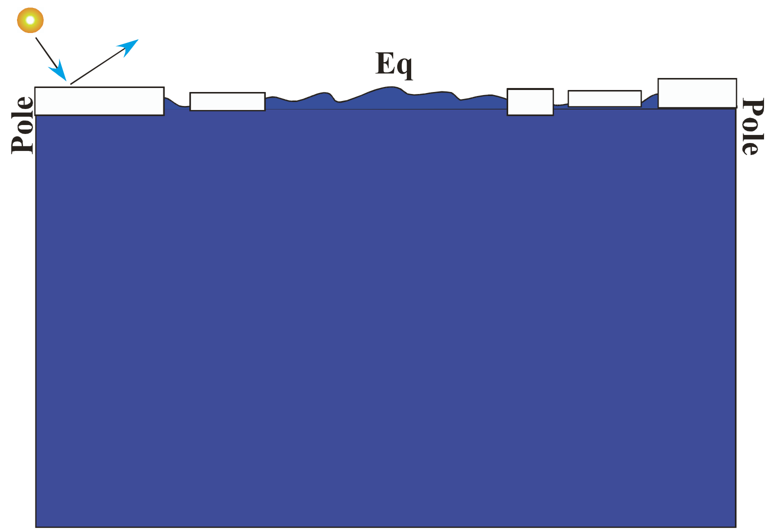
Sea ice albedo feedback: ”Normal” ice

(e.g. CO_2 or methane) Ice denser than liquid!



Sea ice albedo feedback: Water ice

Water ice lighter than liquid!



How to recover from a snowball state?

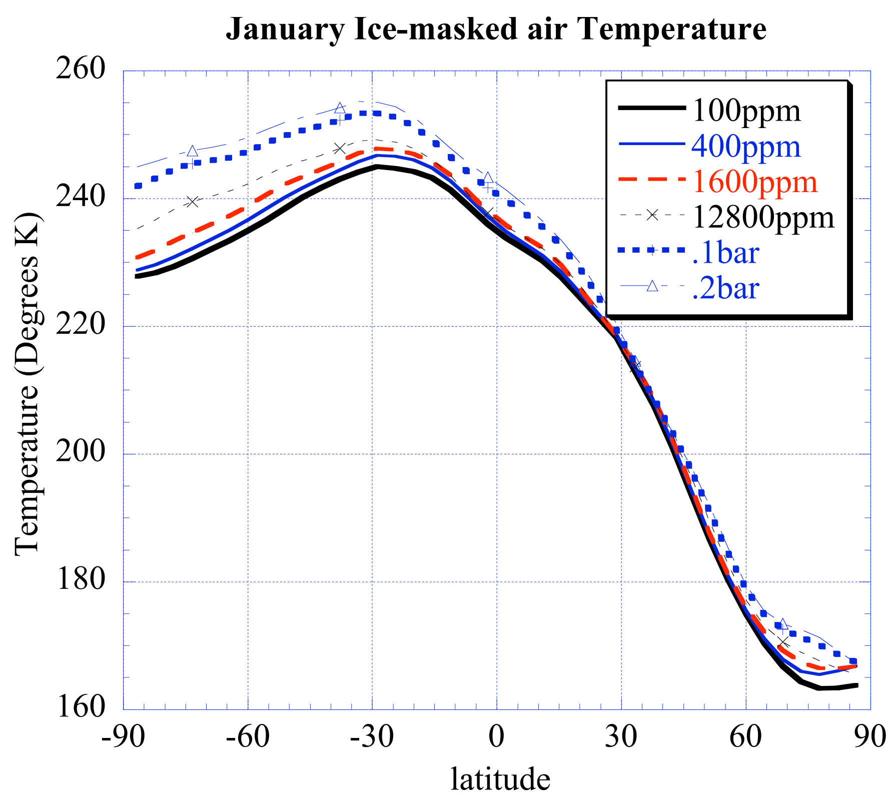
”Snowball” = global thick ice cover on a water ocean.

There are suggestions this may have really happened several times in Earth’s past

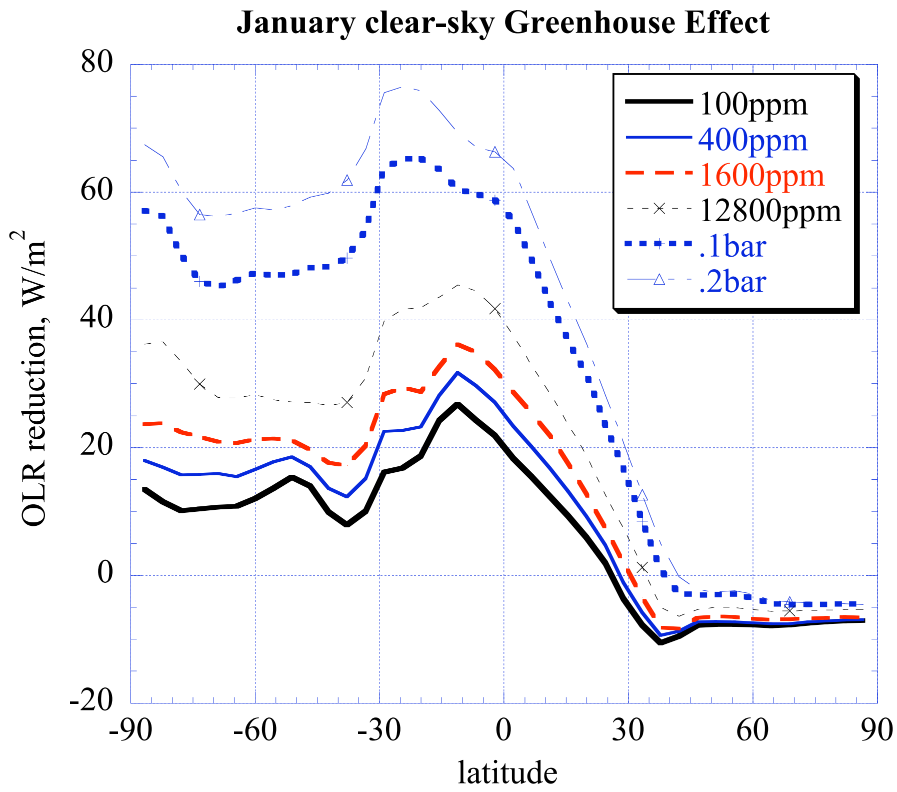
- Increase of solar brightness? Takes too long, maybe forever
- On a tectonically active planet, outgas CO_2 until greenhouse effect causes deglaciation.
- Warm up to metastability point with CO_2, then wait for an asteroid.

GCM simulations of snowball deglaciation

Pierrehumbert, *Nature* 2004, *J. Geophys Res* 2005.

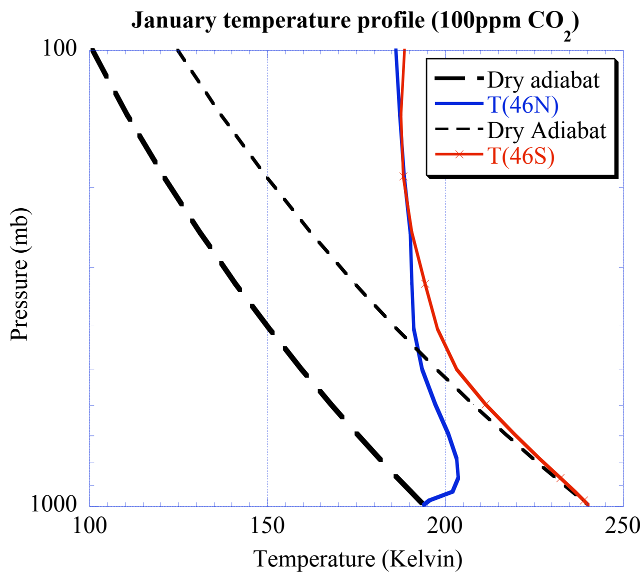

January Ice-masked air Temperature
Temperature (Degrees K)
260
240
220
200
180
160
-90
-60
-30
0
30
60
90
latitude
100ppm
400ppm
1600ppm
12800ppm
.1bar
.2bar

Weak clear-sky greenhouse effect

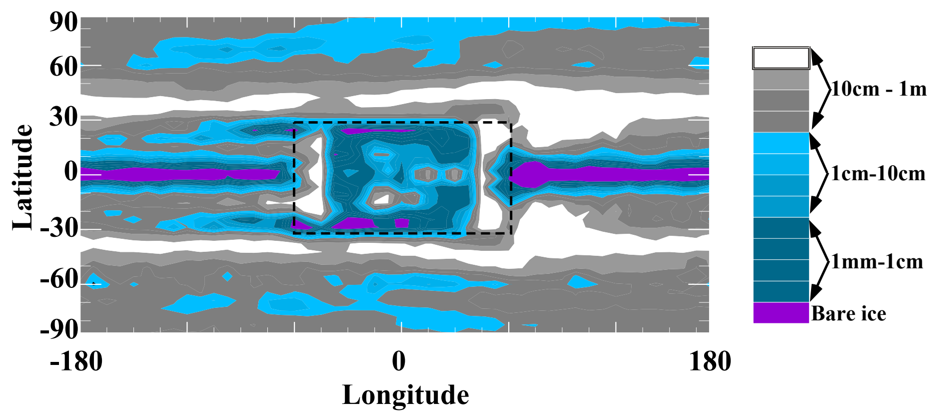


(but cloud greenhouse effect is both important and uncertain)

...due to subtle lapse rate effects



And the planet becomes dusted with highly reflective snow



Atmospheric mass loss mechanisms

- Rayleigh-Jeans ($v \sim \sqrt{(kT/m})$; compare to escape velocity)
- Large asteroid/comet impacts (more loss for small planets)
- Silicate weathering, a *pas des deux* between CO_2 and water

Chemical atmosphere loss on a tectonically dead world

$$CaSiO_3 + CO_2 + H_2O \rightarrow CaCO_3 + SiO_2 + H_2O + \Delta E$$

Warm world without tectonic recycling of crust will sequester CO_2 in crust until it cools down enough that rain stops.

But it happens slowly

... and takes only a little energy (but maybe a lot of intelligence) to reverse.

Example: On Earth at present

- Each year, $10^{-6} Moles/m^2$ of CO_2 turn into rock
- Requires $10^{-6} W/m^2$ to cook the CO_2 back out of the rock. (heat .1g of rock to 600K once per year).
- Compare with 240 W/m^2 of absorbed solar energy

A few things we've learned

- A water ocean is a bane as well as a blessing: It makes one subject to both a snowball crisis and a runaway greenhouse crisis.

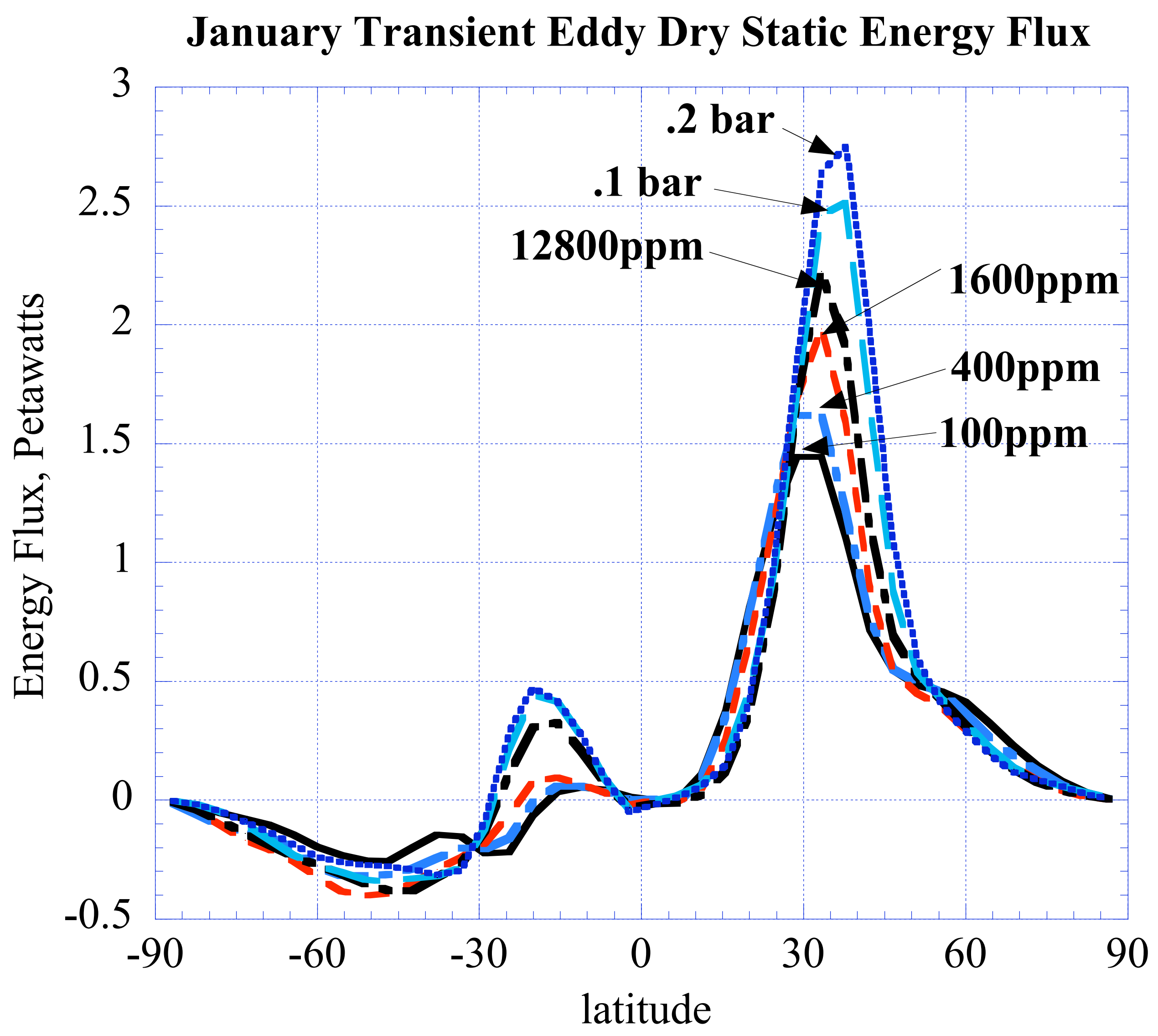
  Waterworlds need an additional greenhouse gas which participates in a stabilizing loop (e.g. CO_2 and silicate weathering)

- The best current calculations indicate that it is difficult, and perhaps impossible, to recover from a snowball crisis. However, there's much more to be learned about the deglaciation problem.

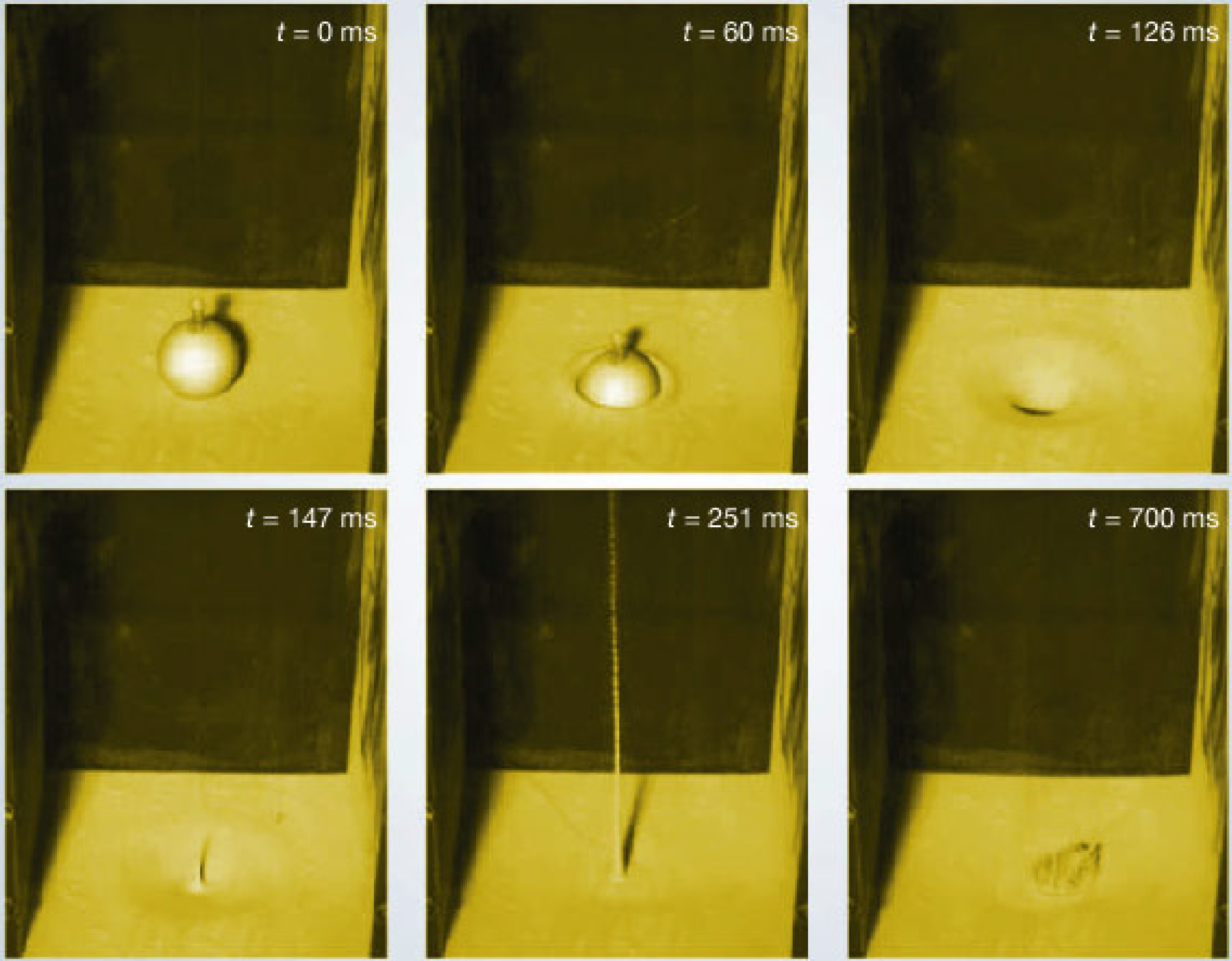
- A wide variety of other substances lead to collective radiative/thermodynamic phenomena entirely analogous to water, though generally at lower temperatures. Our notion of the distinguished place of water is biased in part by its role in ”life as we know it.” CO_2 worlds go into a runaway state before they can support a liquid CO_2 ocean, but methane worlds can support a liquid methane ocean.
- Water does have some distinguishing features, though: Water ice sinks, and water catalyzes the silicate/CO_2 weathering reaction.
- We are only beginning to understand other binary greenhouse atmospheres with interesting chemistry (e.g. the methane/CO_2 system)
- Clouds are important everywhere, and are everywhere problematic

A few mathematical opportunities

- Infrared scattering with gaseous absorption. A problem in non-Markov statistics on random walks
- Heat transport in large scale rotating stratified turbulence on a sphere. Especially influence of static stability on scaling
- Baroclinic instability in the presence of condensible substances which have a large effect on surface pressure Early Mars storms; Dynamic calculations of runaway greenhouse and post-snowball climate
- Suspended cloud condensate in cold convective systems A tracer problem with settling, condensational source and evaporative sink
- Atmospheric mass loss (or gain) during bolide (asteroid,comet) impacts. Formation of jets, and distribution of kinetic energy



January Transient Eddy Dry Static Energy Flux
.2 bar
.1 bar
12800ppm
1600ppm
400ppm
100ppm
Energy Flux, Petawatts
latitude
3
2.5
2
1.5
1
0.5
0
-0.5
-90
-60
-30
0
30
60
90


t = 0 ms
t = 60 ms
t = 126 ms
t = 147 ms
t = 251 ms
t = 700 ms