Outer Limits of the Habitable Zone

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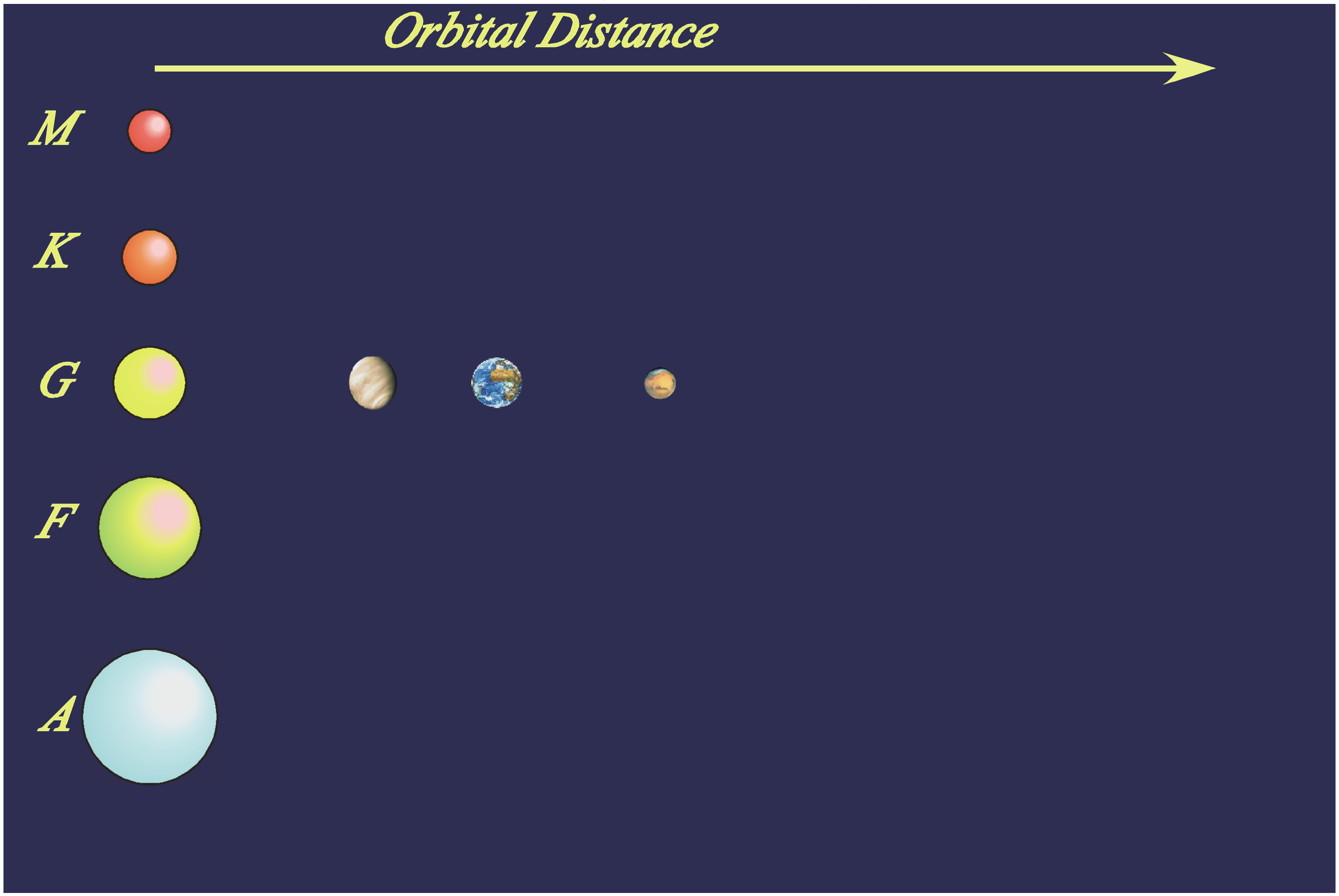
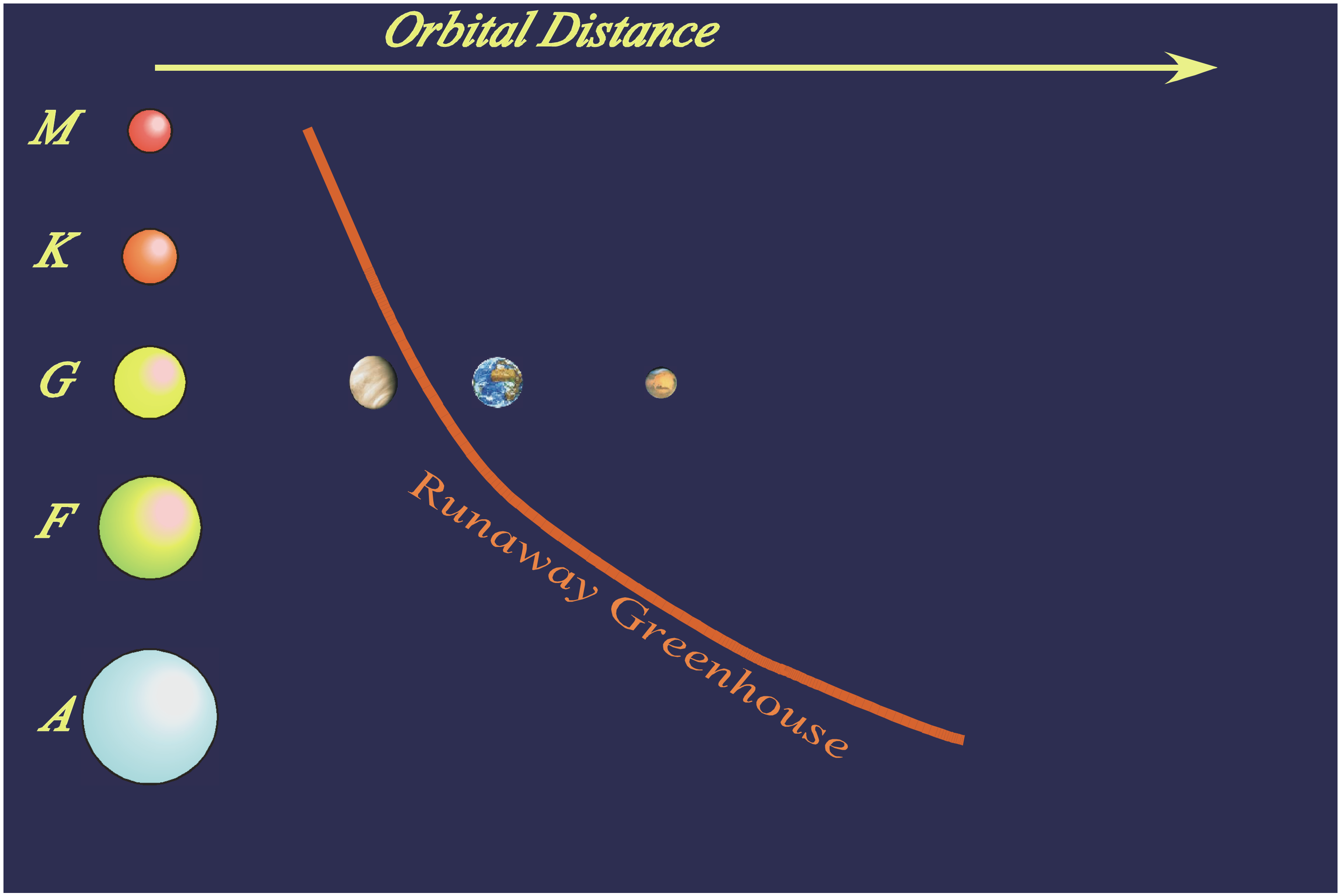
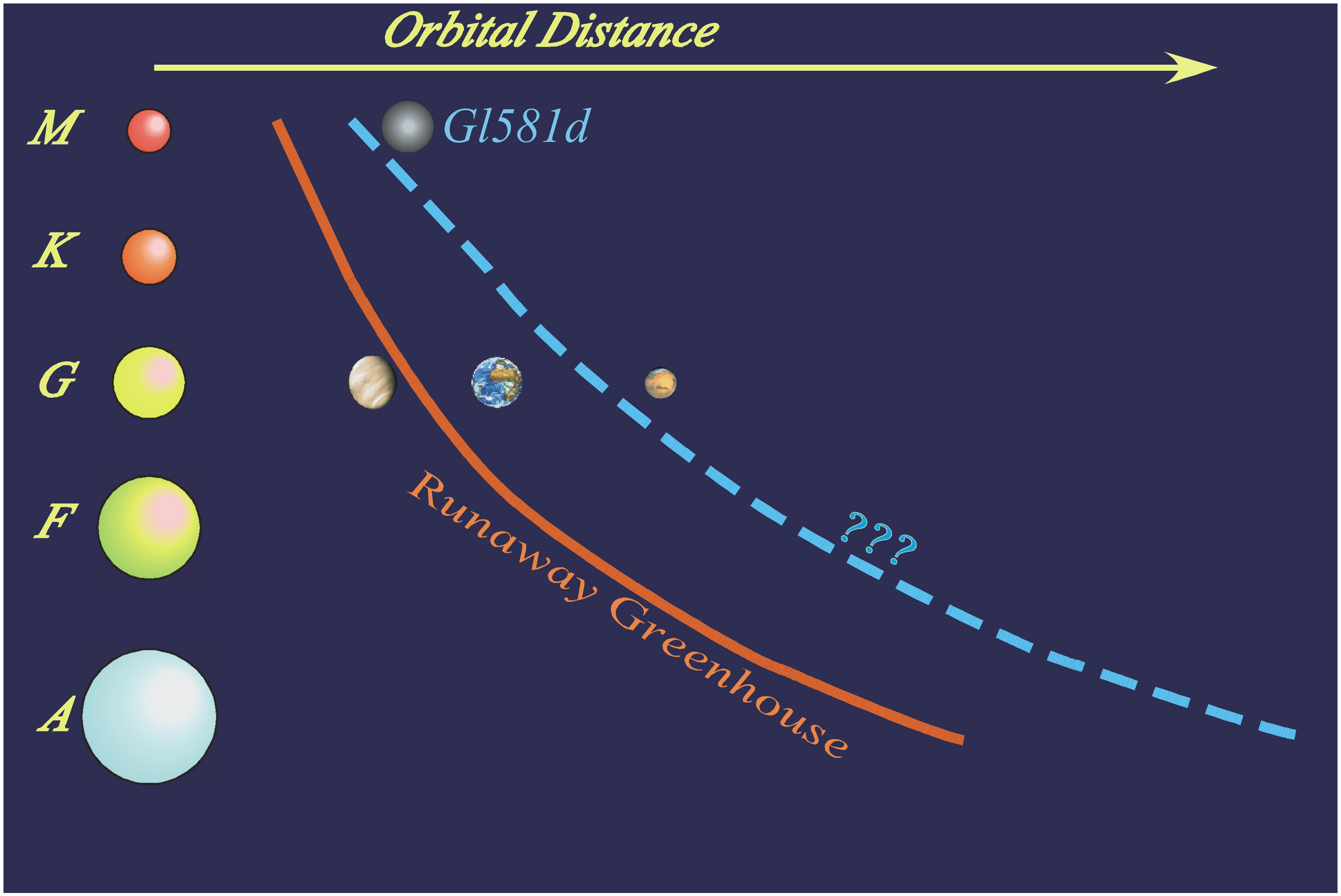
Habitability zones in space



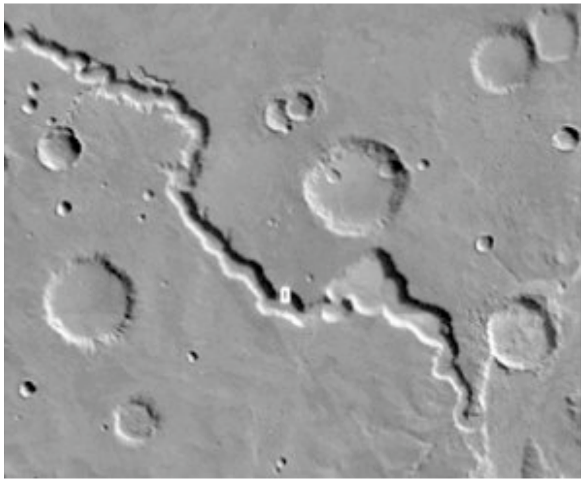
Inner limit for water ocean planet given by water vapor runaway

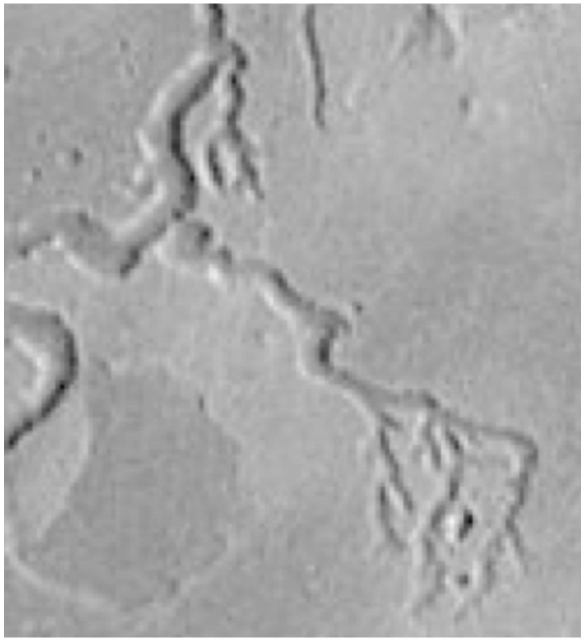


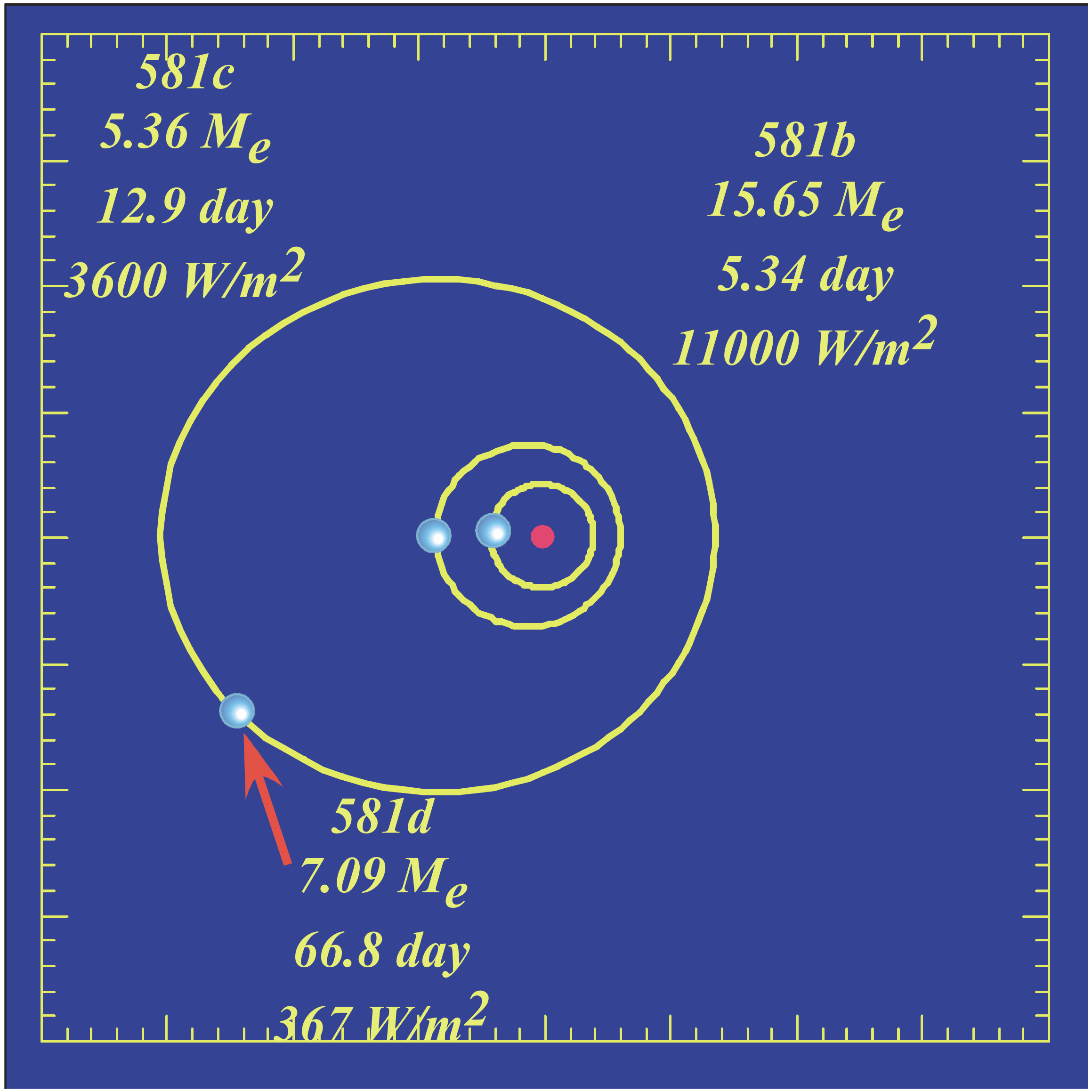
But what determines the outer limit?



A habitable Early Mars?







(vs. 2613W/m^2 Venus, 1367W/m^2 Earth, 589W/m^2 Mars

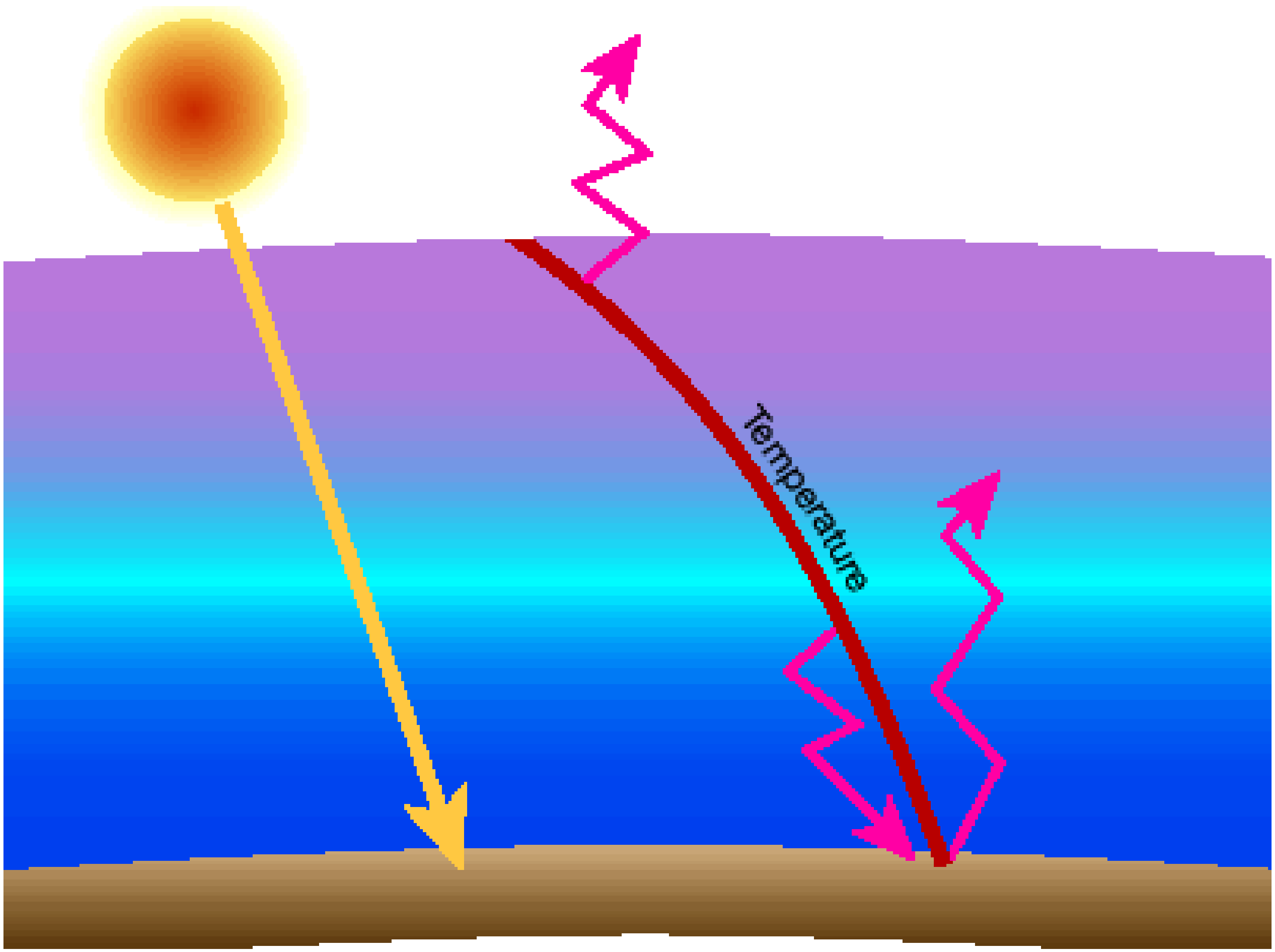
Not obvious there should be an outer limit

Why not just stuff in enough greenhouse gas until it's habitable?

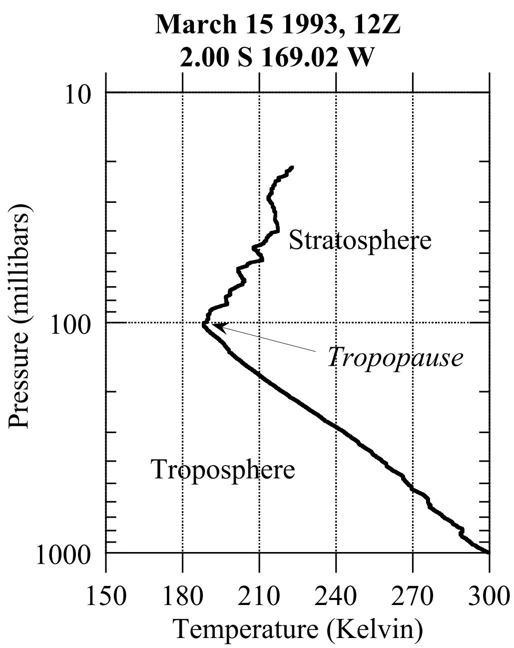
Things that can go wrong

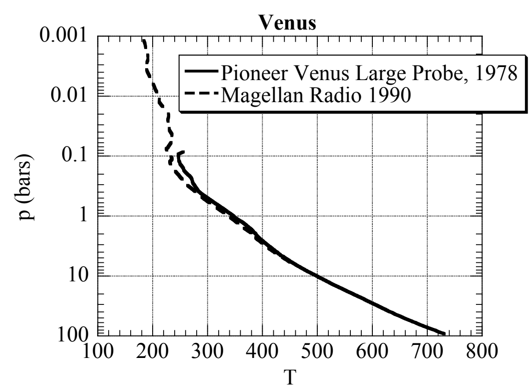
- Rayleigh scattering increases albedo. (Spectrum-dependent!)
- Shortwave-absorbing greenhouse gas leads to anti-greenhouse effect
  - Depends on stellar spectrum
  - Problem with CH_4 already for G stars
  - For M stars, potential problem even with CO_2
  - (But this isn't actually a problem)
- Condensation

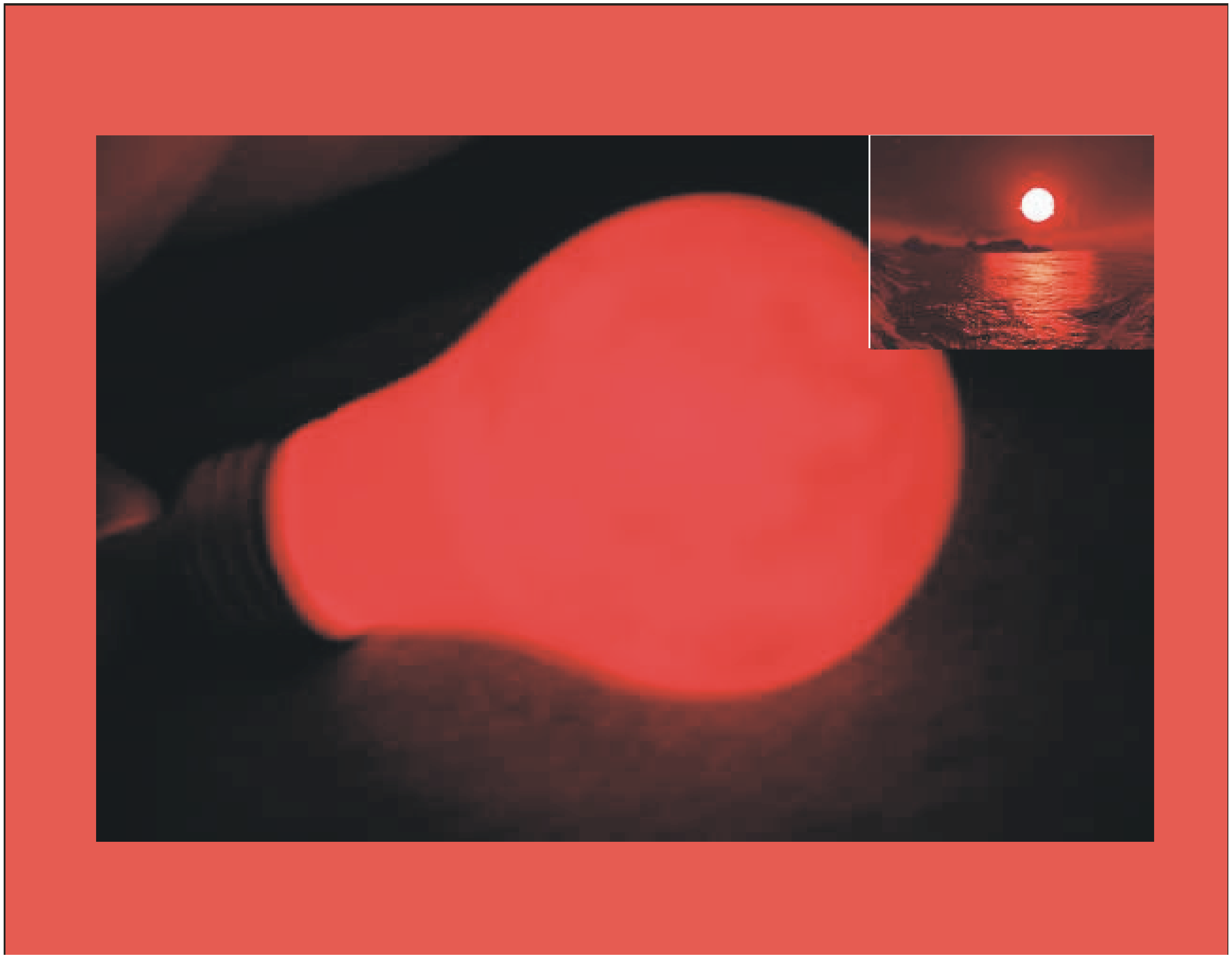
Vertical structure and the greenhouse effect



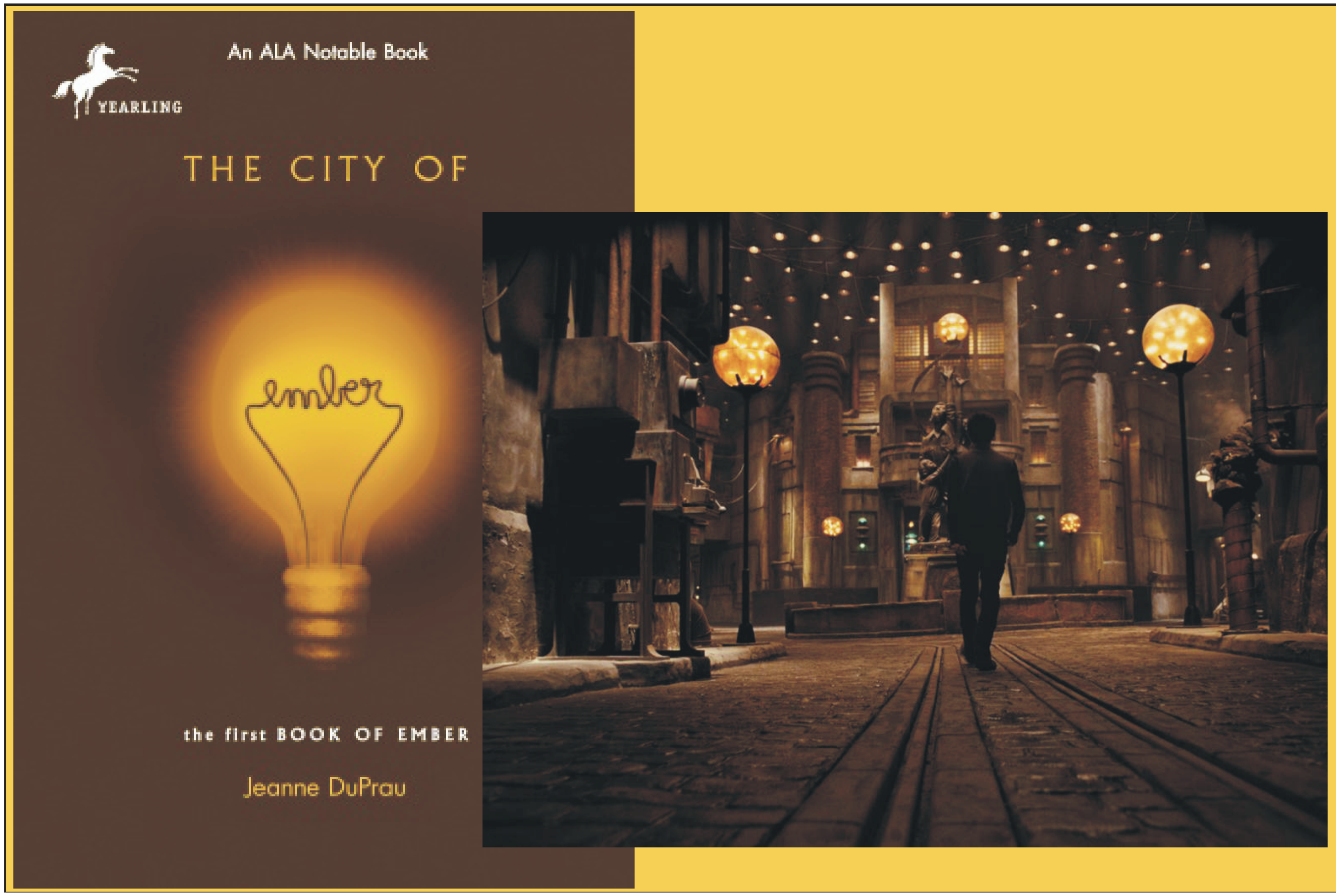
Earth and Venus profiles



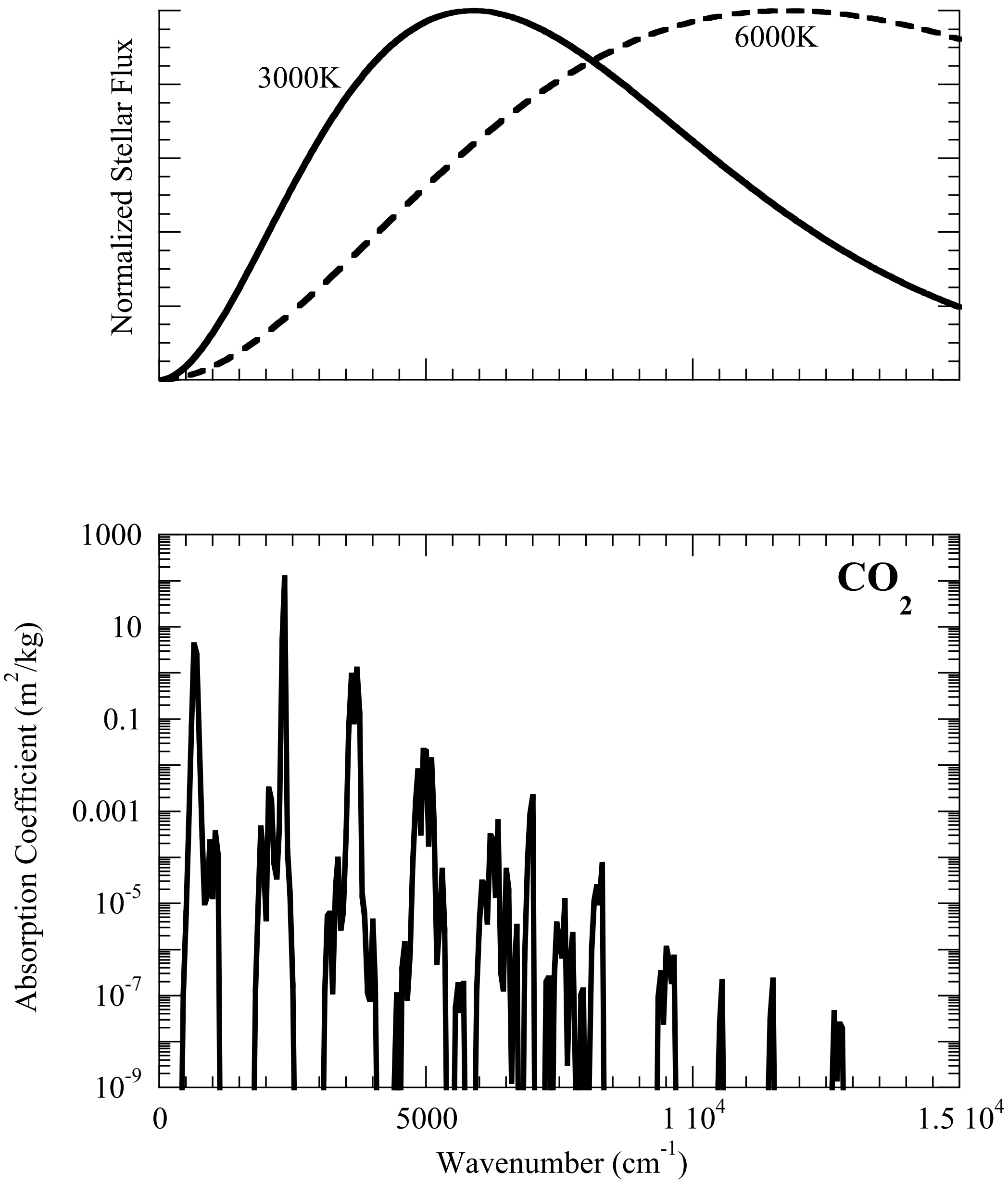




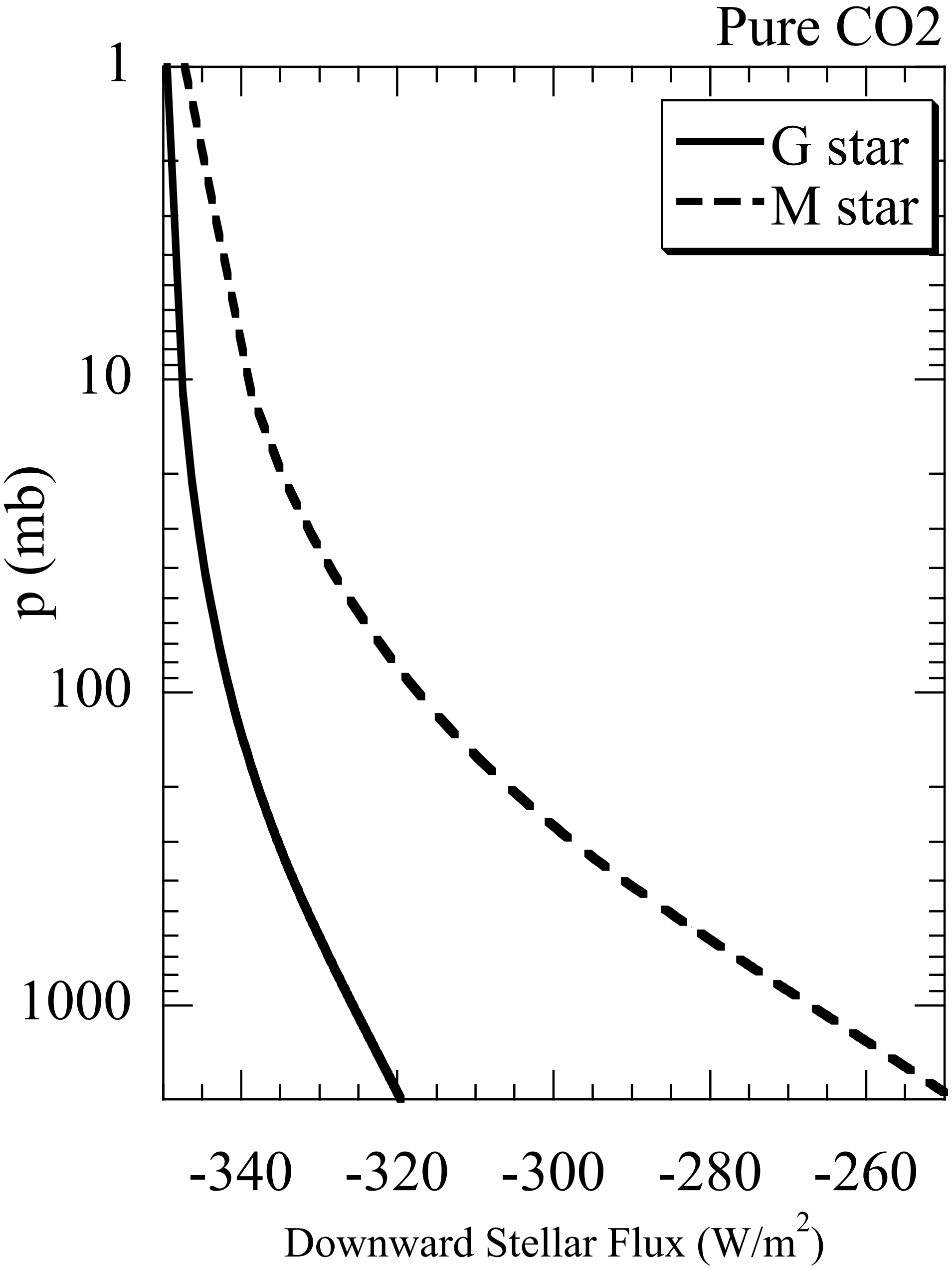
In the Red


An ALA Notable Book
YEARLING
THE CITY OF
ember
the first BOOK OF EMBER
Jeanne DuPrau

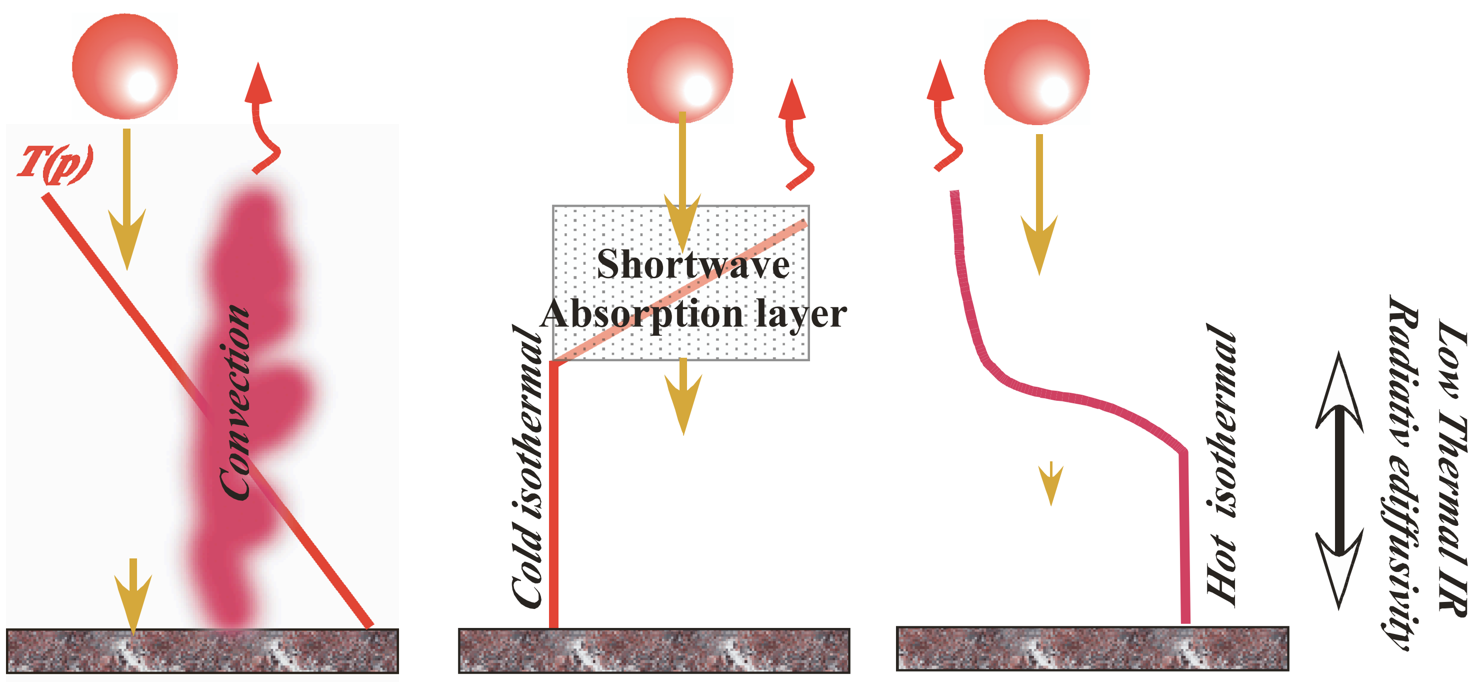
In the Red


Normalized Stellar Flux
3000K
6000K
CO2
Absorption Coefficient (m2/kg)
1000
10
0.1
0.001
10-5
10-7
10-9
0
5000
1 104
1.5 104
Wavenumber (cm-1)

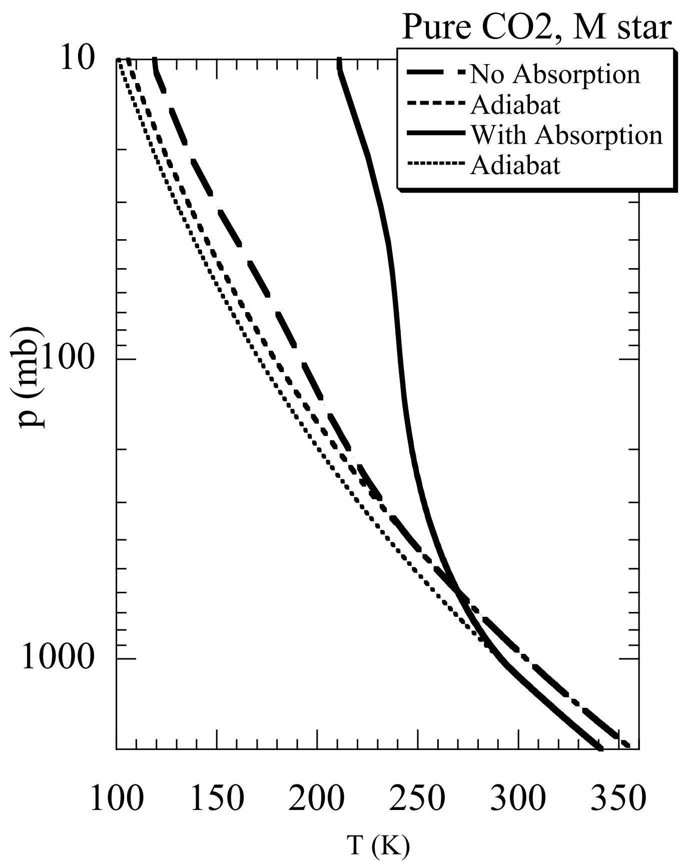
Flux profile


Pure CO2
G star
M star
1
10
100
1000
p (mb)
-340
-320
-300
-280
-260
Downward Stellar Flux (W/m^2)

In the deep and the dark



But actually, we're in the "Venus as Glacier" regime



Things that can go wrong

- Rayleigh scattering increases albedo. (Spectrum-dependent!)
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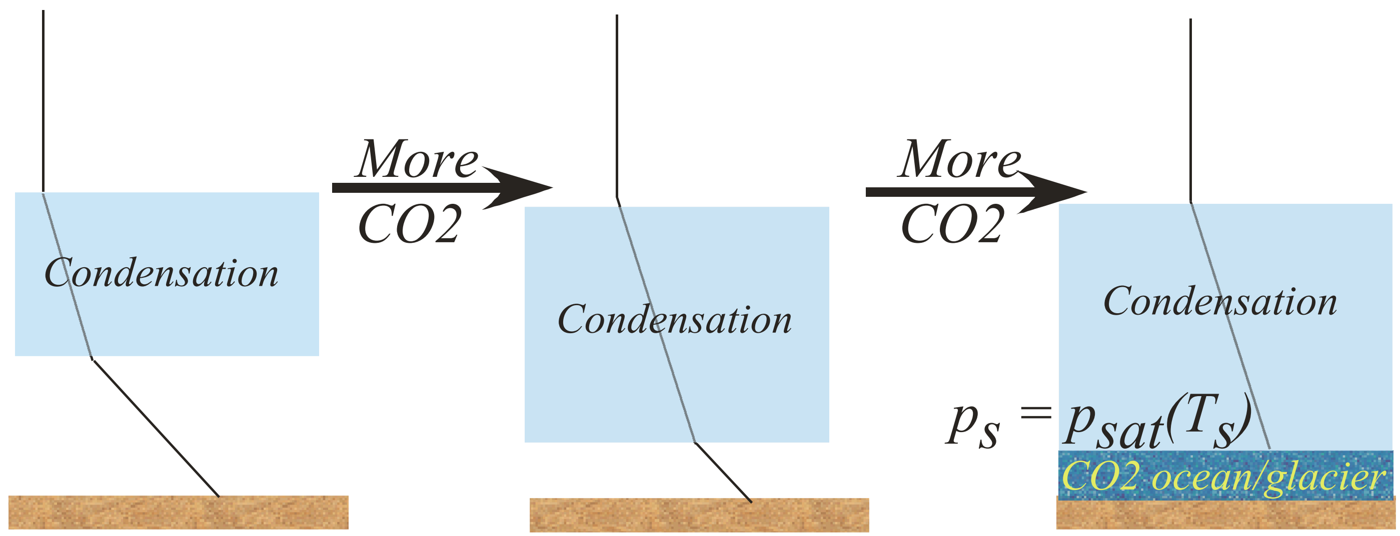
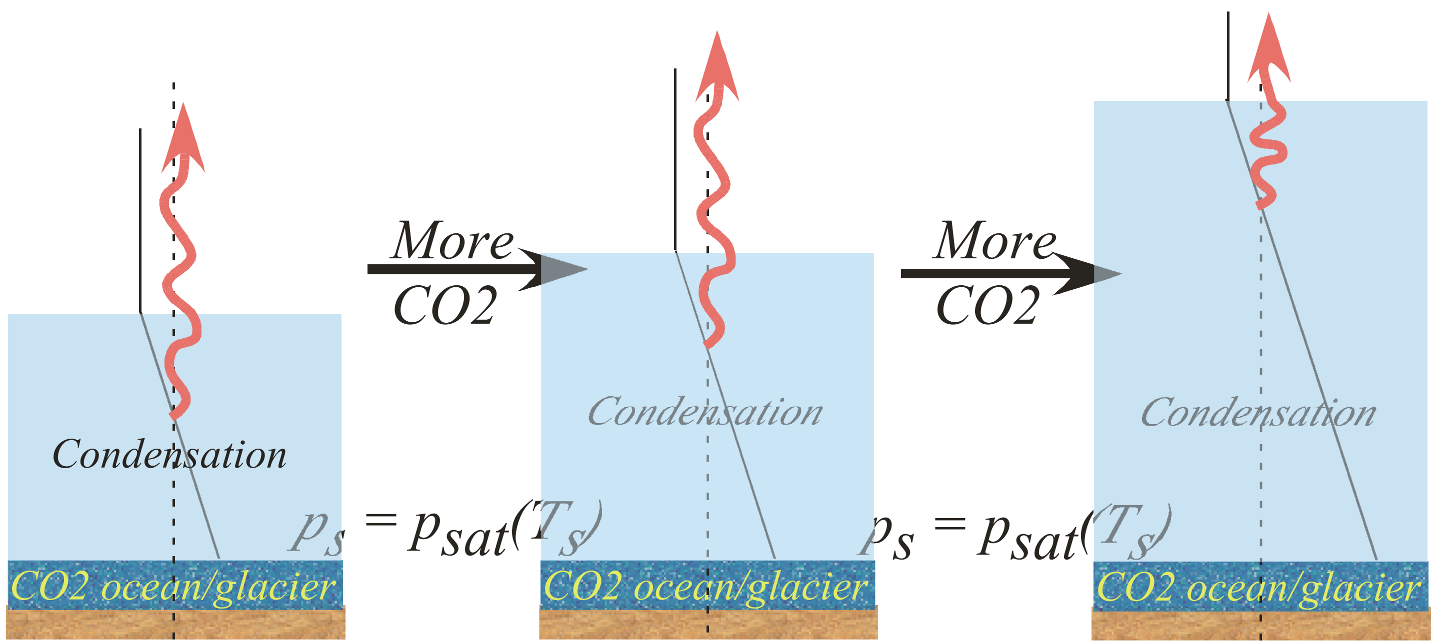
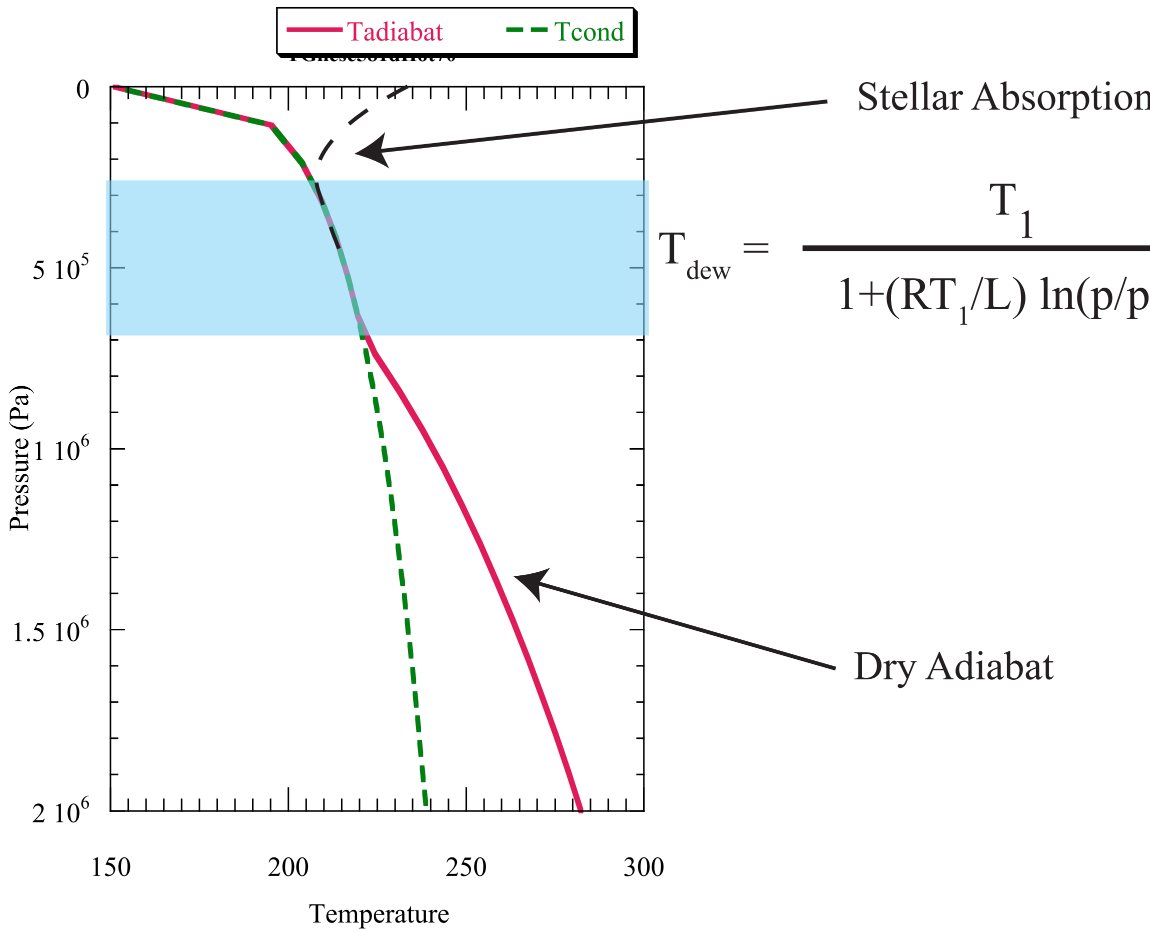
  - Problem with CH_4 already for G stars
  - For M stars, potential problem even with CO_2
  - (But this isn't actually a problem; cf AGU2008)
- Condensation

Here's what happens

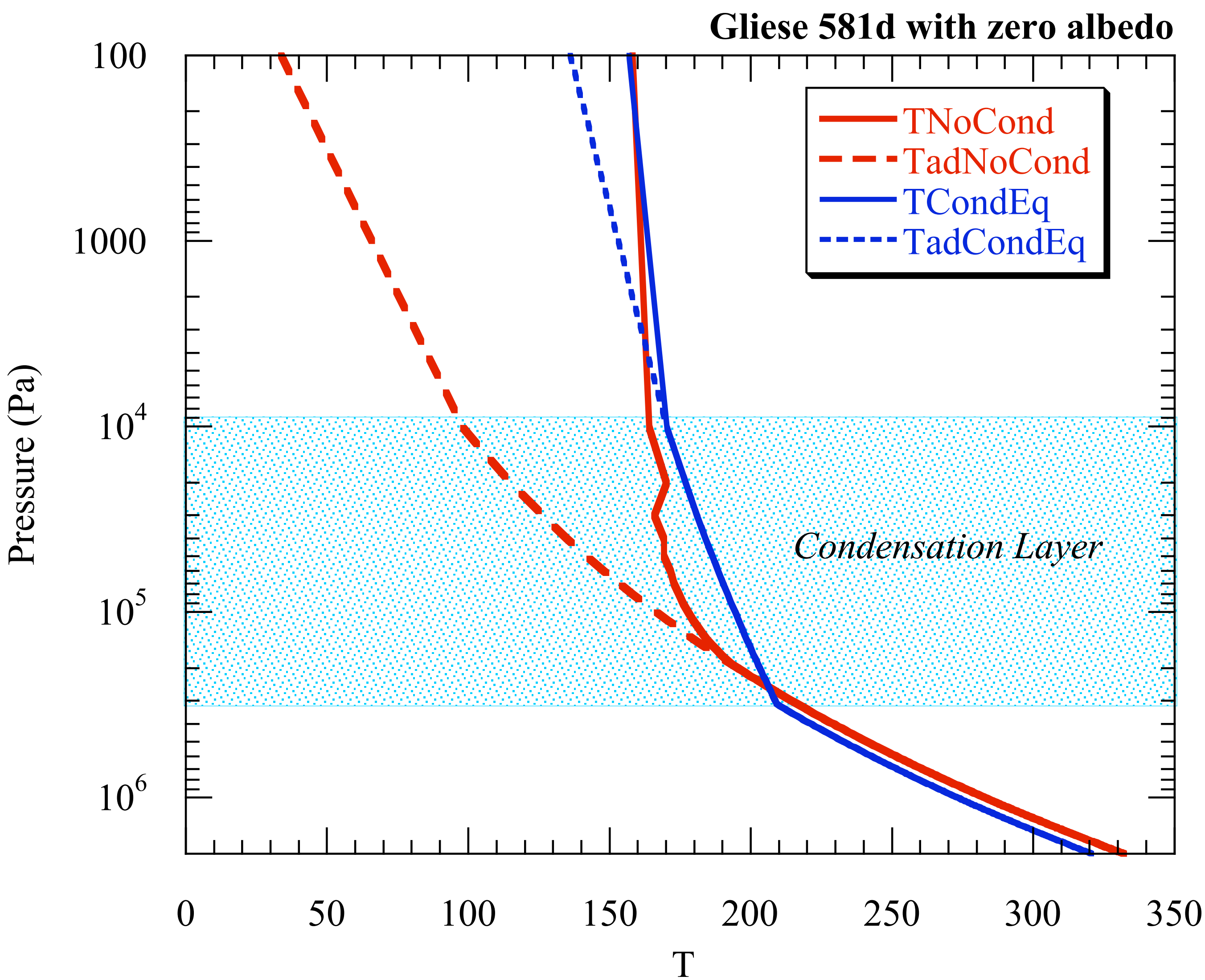


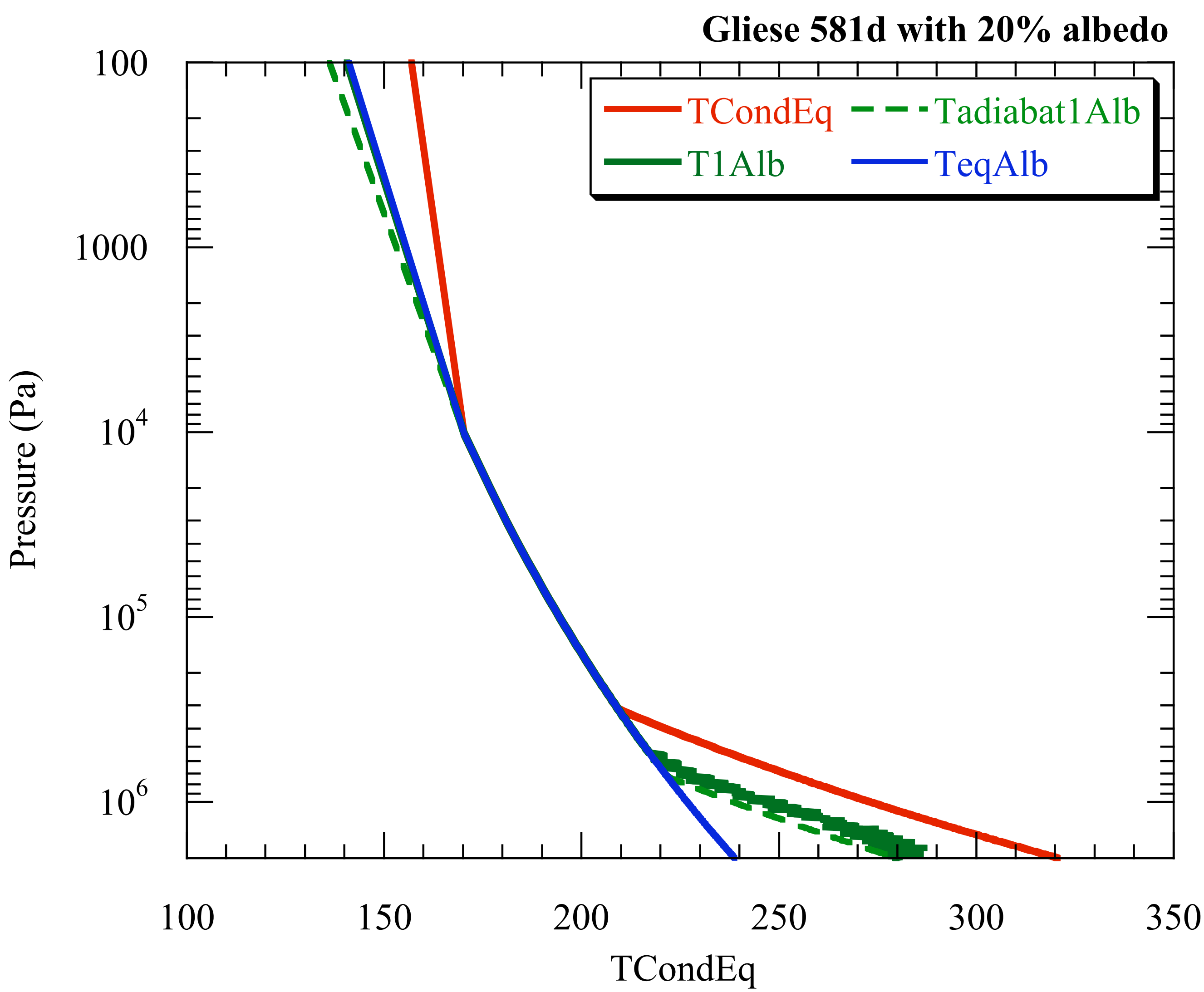
Here's what happens



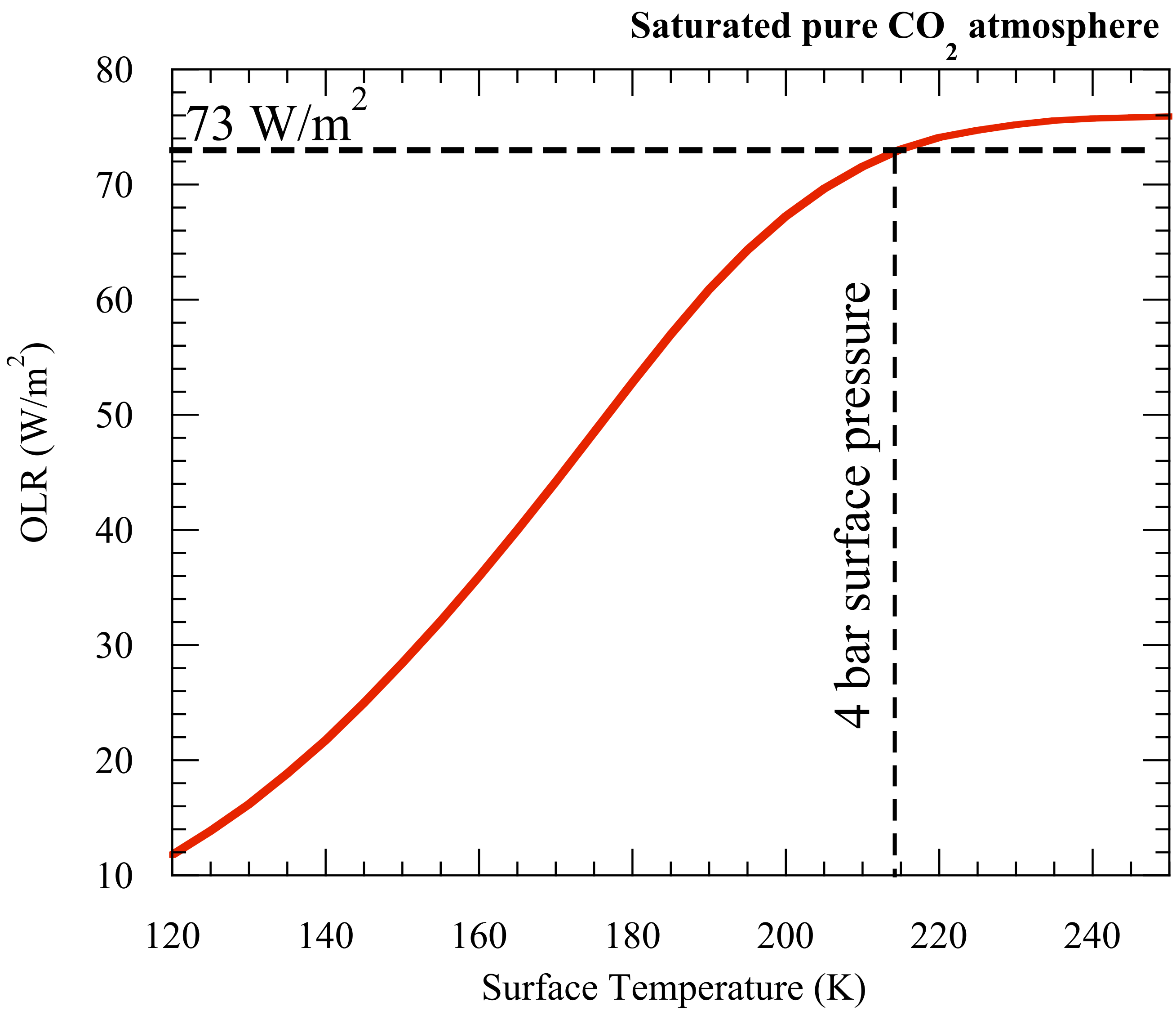


$$T_{dew} = \frac{T_1}{1+(RT_1/L)\ln(p/p_1)}$$


Gliese 581d with zero albedo
Pressure (Pa)
T
100
1000
10^4
10^5
10^6
0
50
100
150
200
250
300
350
TNoCond
TadNoCond
TCondEq
TadCondEq
Condensation Layer


Gliese 581d with 20% albedo
TCondEq
Tadiabat1Alb
T1Alb
TeqAlb
Pressure (Pa)
100
1000
10^4
10^5
10^6
100
150
200
250
300
350
TCondEq

Generalized CO_2 runaway for Gliese 581d

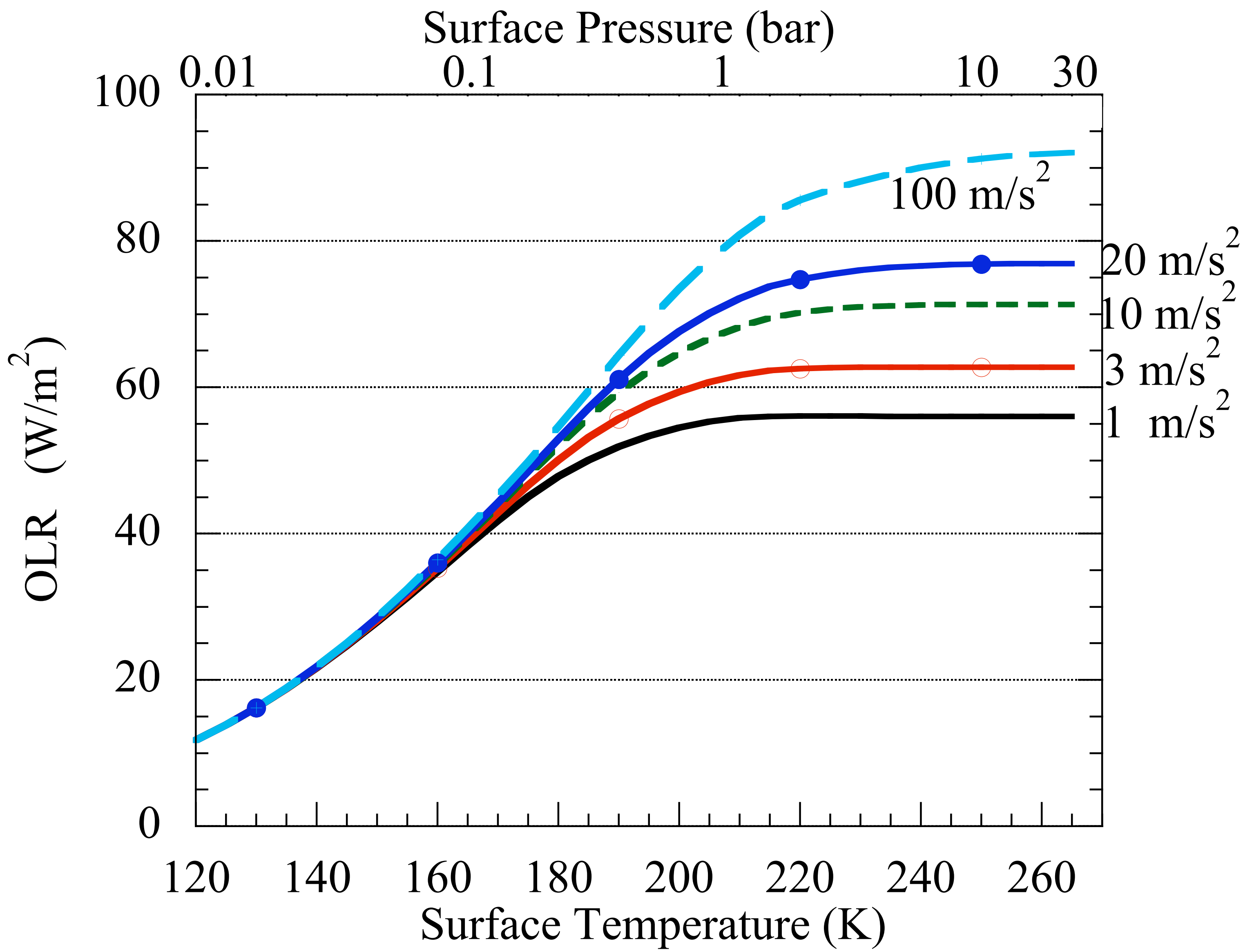


At the Outer Limits...

Runaway is a *good thing* for habitability

(Keeps your atmosphere in the atmosphere)

High gravity makes things worse

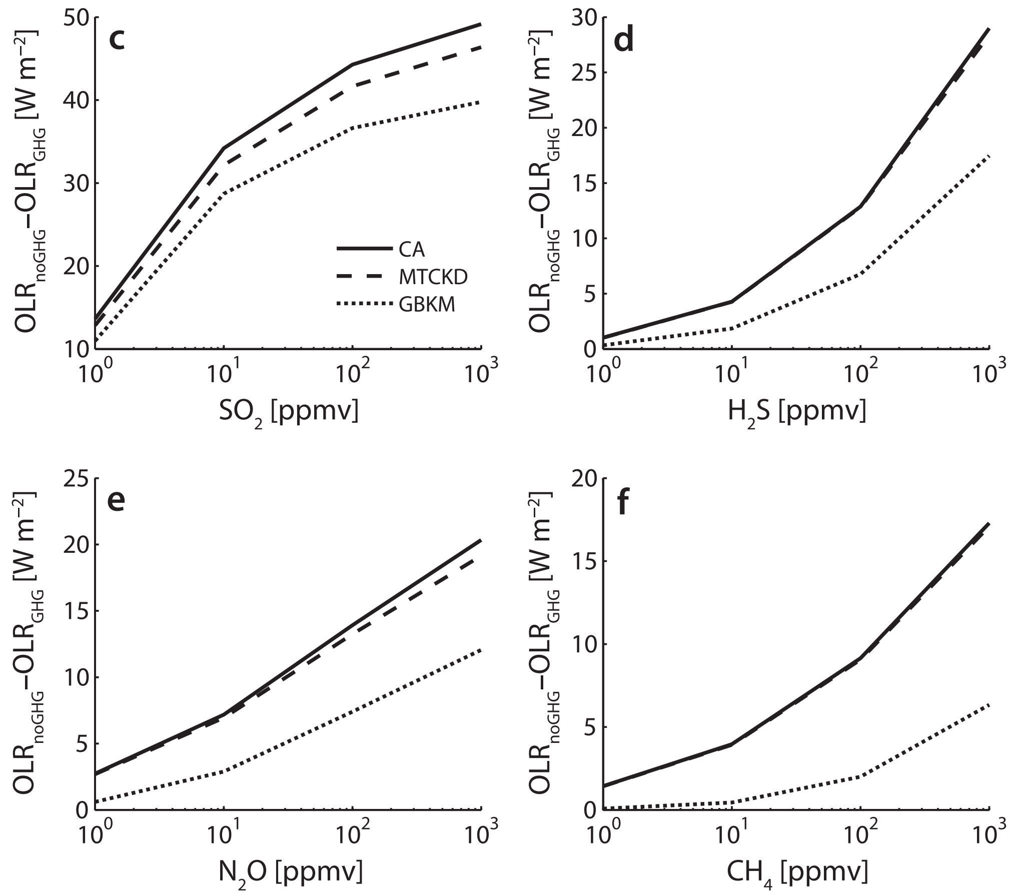


Addition of contaminants can help ..

(if CO_2 gets you most of the way to habitability)

- CO_2 ice clouds (Forget and Pierrehumbert),
- or ...

Halevy, Pierrehumbert and Schrag 2009

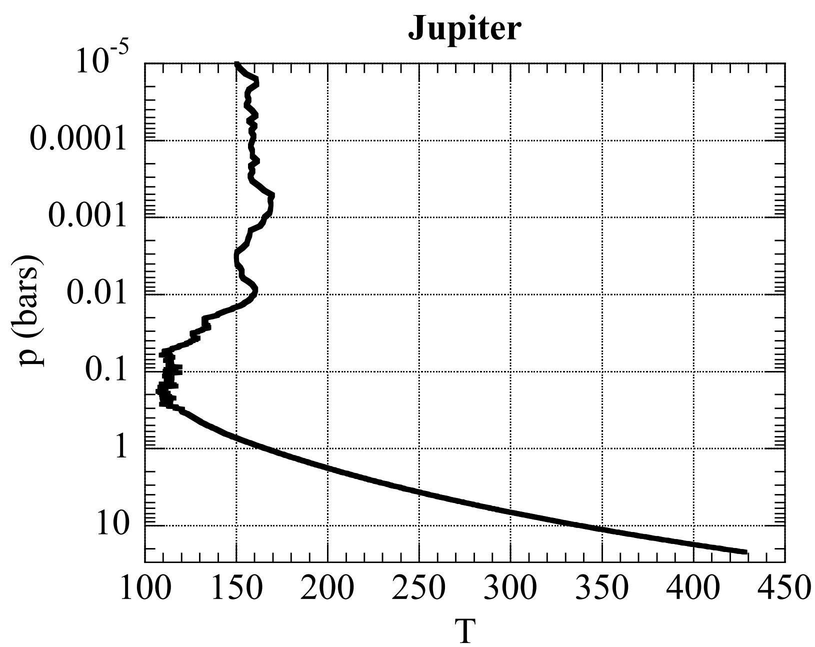


What this world needs is a less condensable greenhouse gas

- CH_4 – Problems: Haze clouds, shortwave absorption
- SO_2? NH_3? – Photochemical, solubility problems
- N_2 at high density
- Jovian-type H_2-dominated dense atmospheres
- Collision-induced absorption critical to much of this

Each of these gases has its own K-I limit.

Small, rocky Jupiters?



Water-habitable at 5 bars, $2.4g_e$!

Small, rocky Jupiters?

A habitable Super-Earth with a 5 bar Jovian-type atmosphere getting 9 W/m^2 of illumination? (about 1 au out from M-dwarf)

But here's the rub

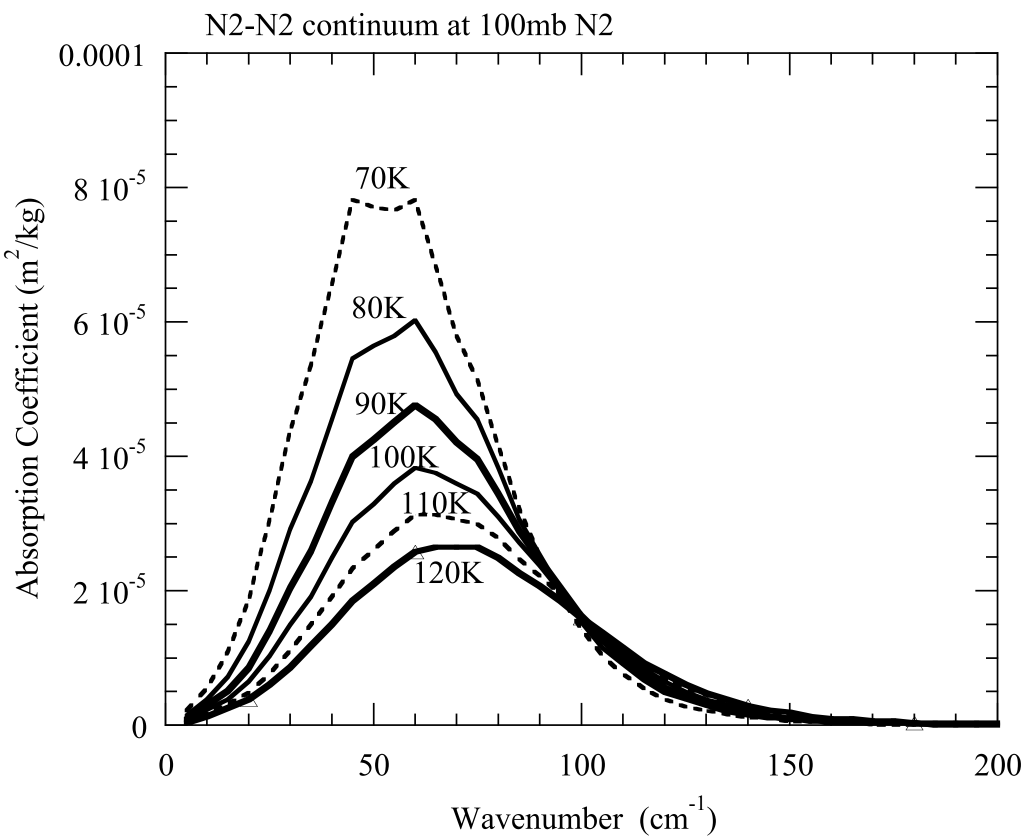
- Escape energy goes like gr
- Super-Earth much smaller than Jupiter
- Unlikely to hold H_2 unless there is a strong interior supply

And now for something completely different

- Cold hydrocarbon lake habitability. (Titan analogues)
- Think Super-Titans about 1au out from Gliese
- It has been proposed (cf. Lunine) that biochemistry could occur in methane/ethane lakes
- For such life, the methane/N_2 runaway is fatal

- Below 90K methane freezes. Titan is near outer limit.
- But mixture with ethane, N_2, etc. depresses freezing point
- But it's also near inner limit
  - 10 bar vapor pressure at 150K
  - Shallow methane lakes would evaporate
  - High gravity would translate into deeper ocean

Maintaining Titanlike conditions involves N_2 CIA runaway



.06 bar at 60K, 1.4 bars at 80K, 10 bars at 100K,

Conclusions: Surface water habitability

- Condensation limits on the outer edge of habitability are determined by a generalization of the runaway greenhouse to gases other than water vapor.
- Early Mars and Gliese 581d are near the threshold where CO_2 could make make the planet water-habitable.
- Spicing up the atmosphere with clever, exotic stuff can push it over the threshold, but it doesn't take much to hold these planets back, either.
- For insolation much below Marslike values, CO_2 becomes ineffective at maintaining water-habitability. Most other gases that could step in to replace it have serious problems.
- Small Rocky Jupiters an interesting possibility, but dubious whether they could hold their H_2.

Conclusions: Hydrocarbon lakes and Super Titans

- Outer limit of cold hydrocarbon lake hab. zone given by methane triple point, or depressed triple point for mixtures.
- Inner limit given by methane/N_2 runaway. Somewhat over $5W/m^2$ illumination, but needs more careful mapping out.
- Need to keep the N_2 in the atmosphere, but keep some methane left in the lakes/oceans.
- These things would be at 1 A.U. for an M-dwarf (Lunine)