Venus Climate Evolution

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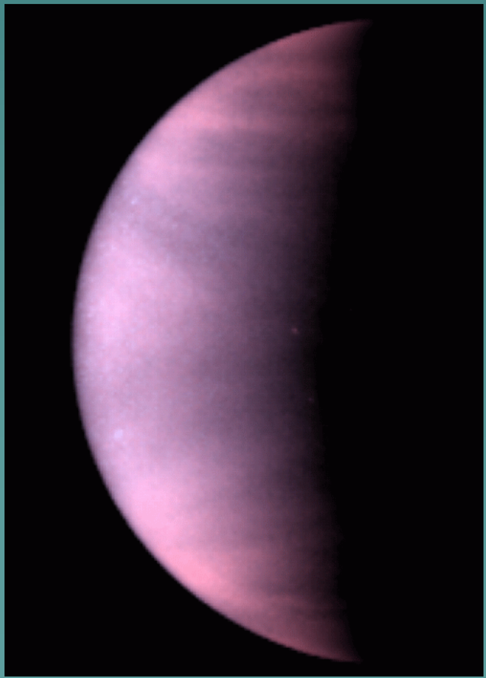
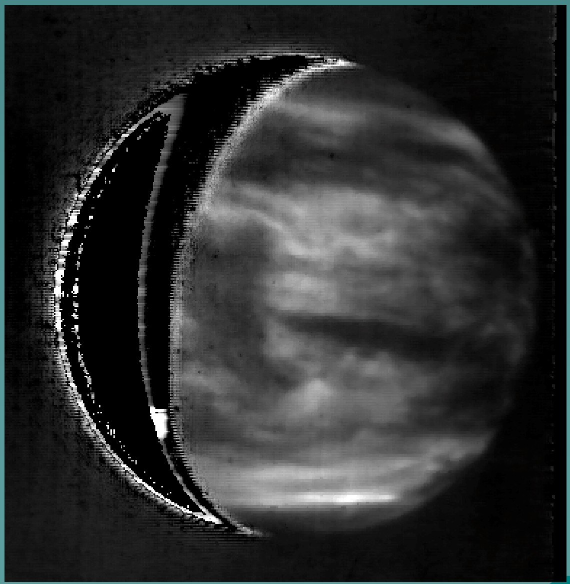
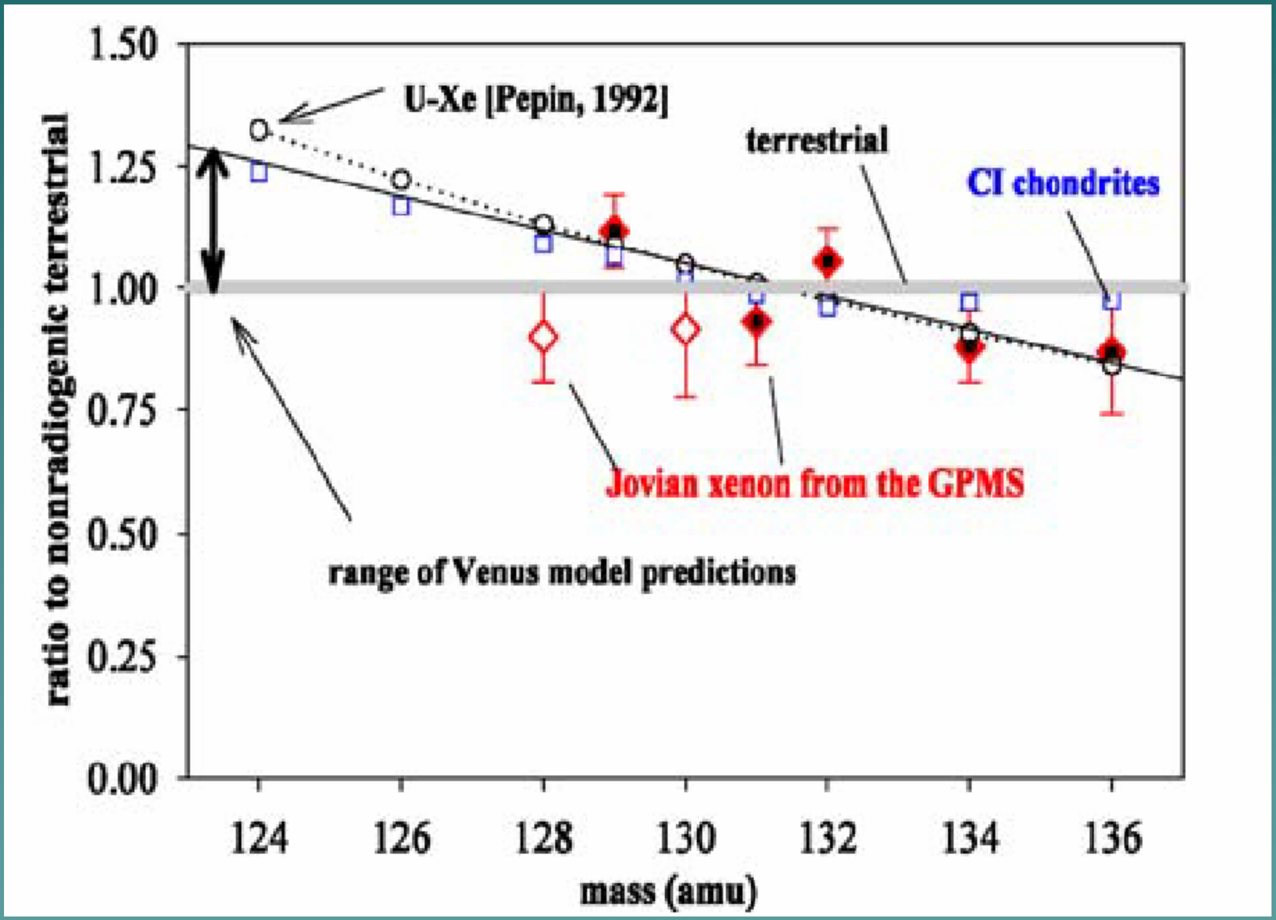




Origin of the Atmosphere

- PV found that Venus' noble gases do not follow the pattern found for Earth, Mars, and meteorites.
- Non-radiogenic Ne and Ar are greatly enhanced.
- Both Ne and N in Earth's atmosphere are heavy, indicating fractionating loss in the past.
- Xe isotopes in Earth's atmosphere are also strongly mass fractionated.

Xe Comparison



- Radiogenic Xe is depleted on Earth.
- Measurements of Xe isotopes on Venus will tell us if the atmosphere is largely, from CI, solar, or U-Xe.
- Thus, we can obtain information on whether Venus' atmosphere experienced massive escape in the past.

Moist Runaway greenhouse

- Warm oceans persisted for a few 100 My while the atmosphere had > 10% H_2O and hydrodynamic escape.
- When atmospheric H_2O became low enough, D/H fractionation began. Carbonation of the surface.
- As Venus lost its surface water, carbonates decomposed and volcanism returned most of the CO_2 to the atmosphere.

Longevity of an Early Venus Ocean

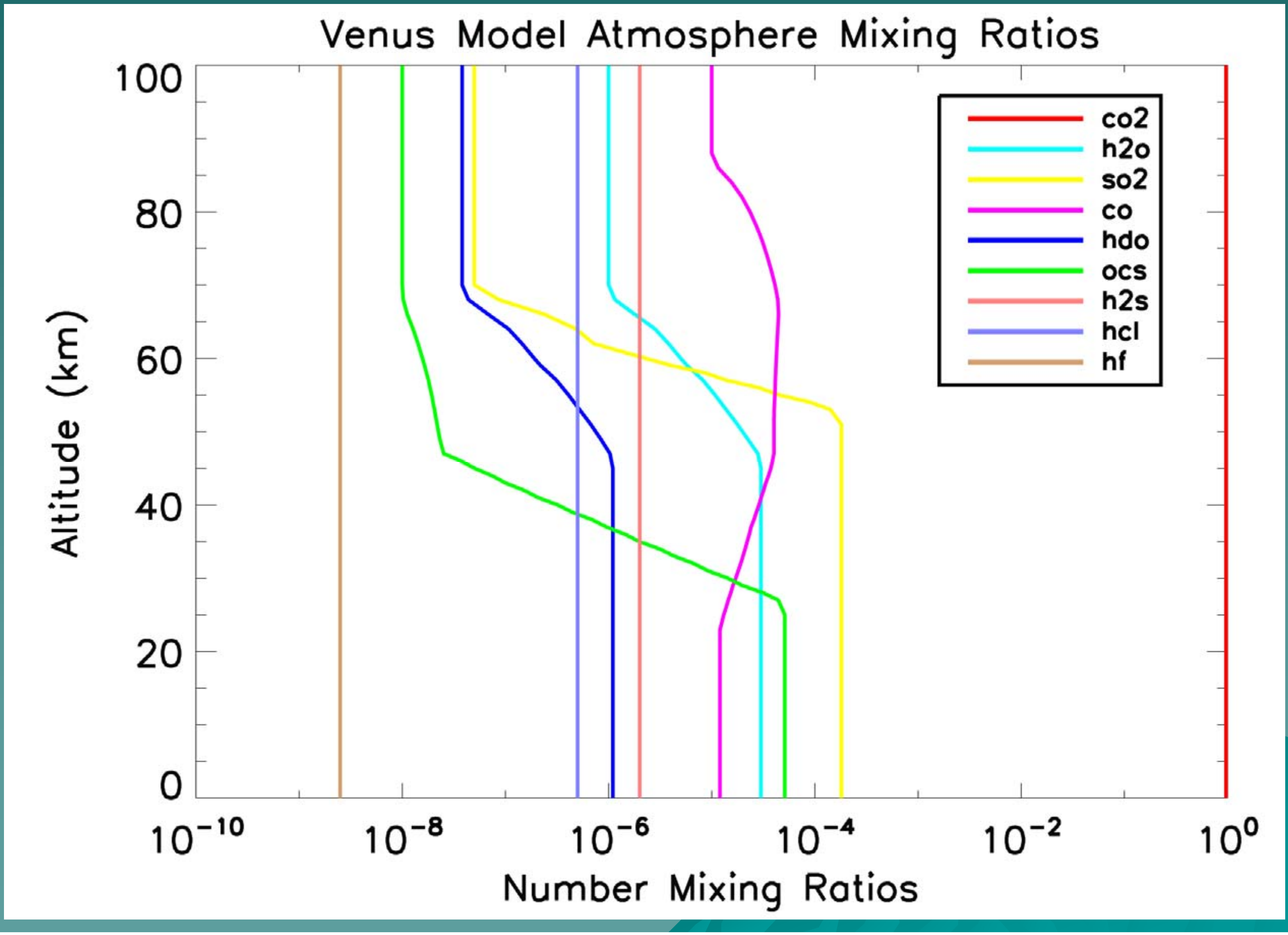
Kasting (1988) in many ways optimized to get rid of ocean quickly:

- Calculations produce **upper limit** on surface temperatures (and therefore upper limit on escape fluxes, and lower limit on lifetime of ocean).
- **Clouds excluded**No cloud feedback which, qualitatively, is expected to stabilize surface temperatures with rising solar flux, and therefore extend the lifetime of the moist greenhouse.
- Preliminary new results suggest that the oceans of Venus may have persisted for ≈ 2 Gy.

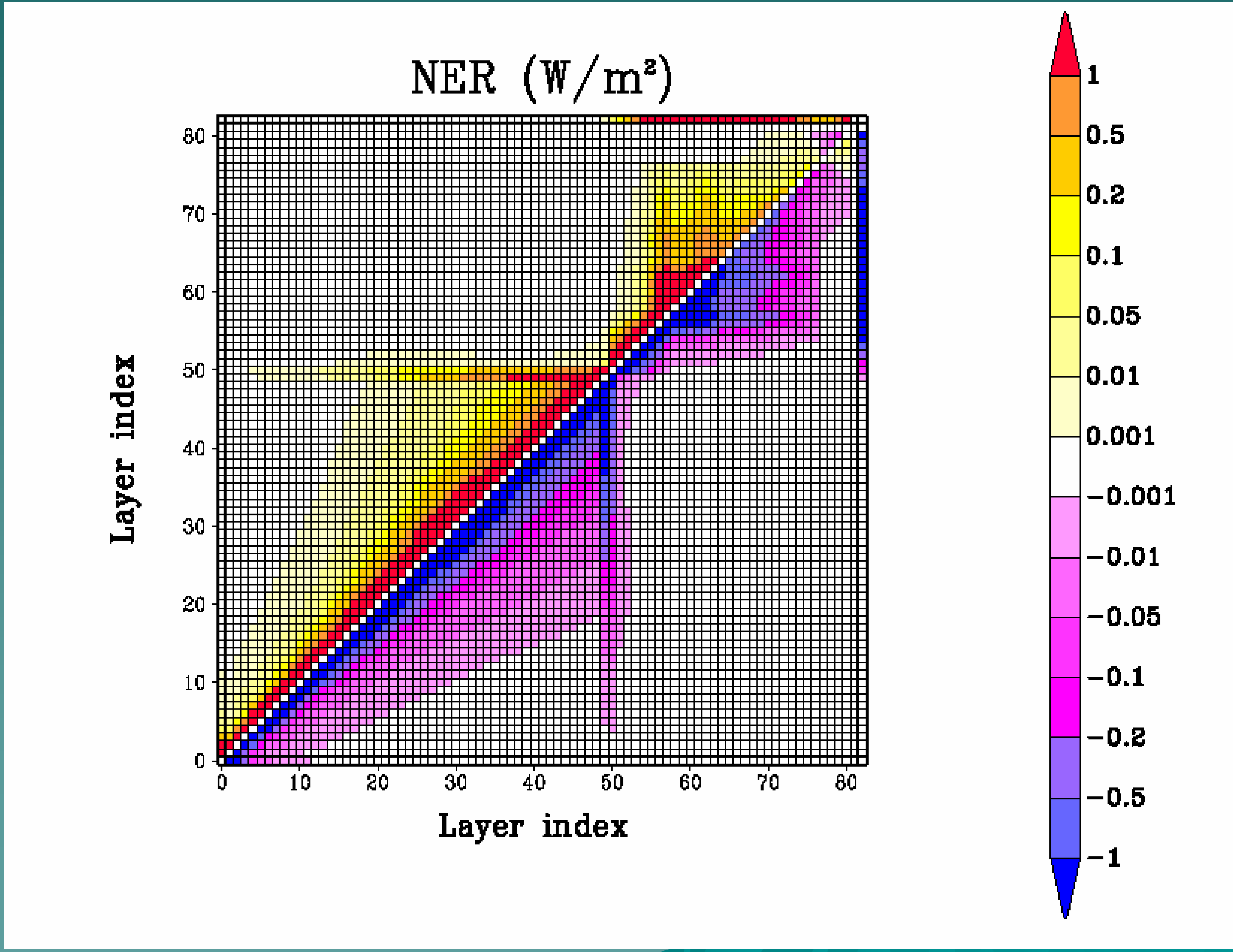
Theoretical Sensitivity of Atmosphere

- Venus' thermal opacity due primarily to pressure broadened CO_2 bands.
- Small amounts of H_2O and SO_2 help fill the gaps in the CO_2 absorption.
- However, H_2O and SO_2 are also the chemical precursors of Venus' bright clouds.
- Therefore, small changes in H_2O and SO_2 may induce large changes in surface temperature.

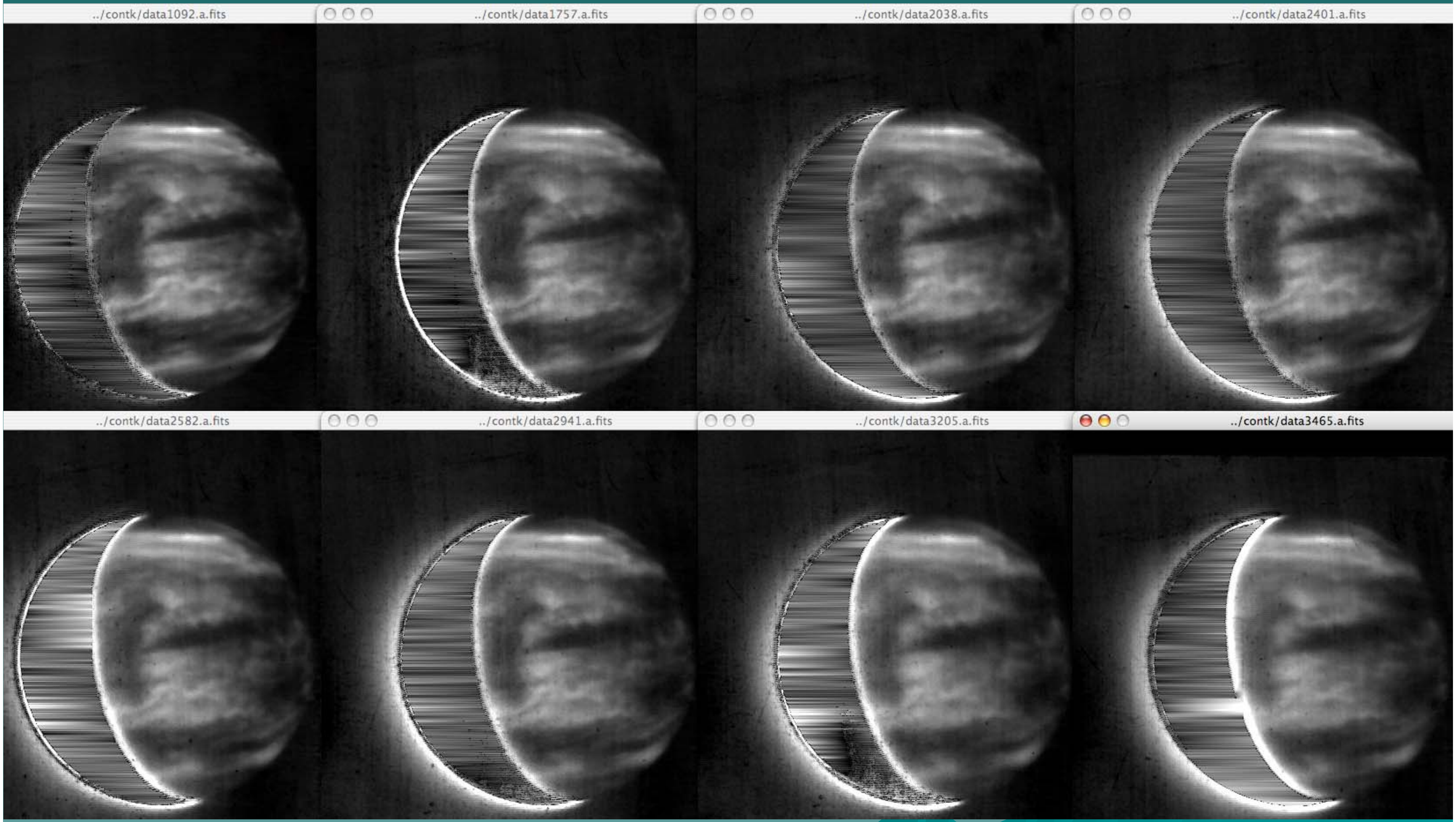
Atmospheric Composition



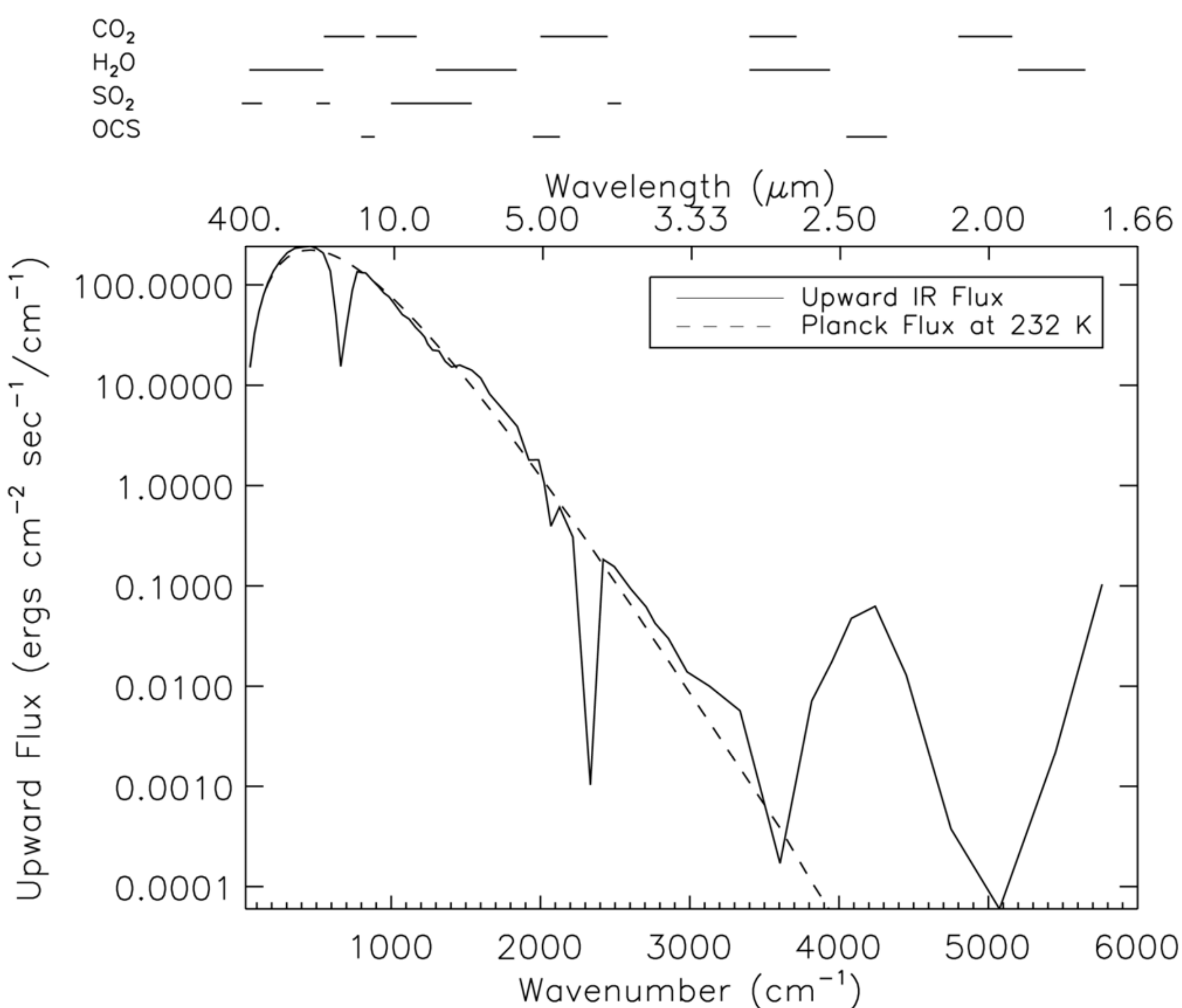
Net Exchange Rate Calculations of Eymet *et al.*



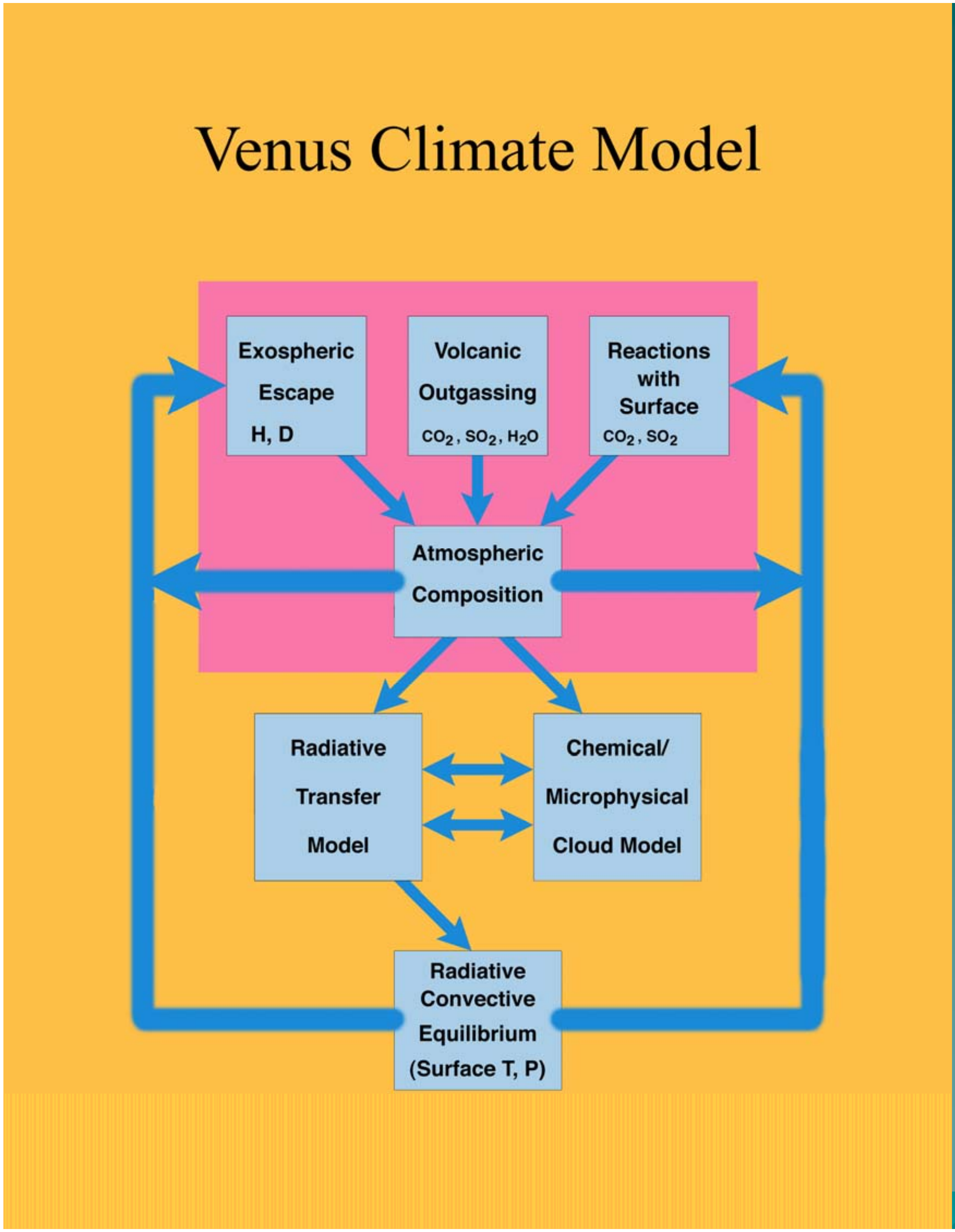
Lower Cloud Variability



Venus Thermostats I



- Significant window between 2.1 and 2.7 μm.
- If Venus' surface heats up, peak of Planck function shifts towards this window.
- This limits how hot Venus' surface can get.



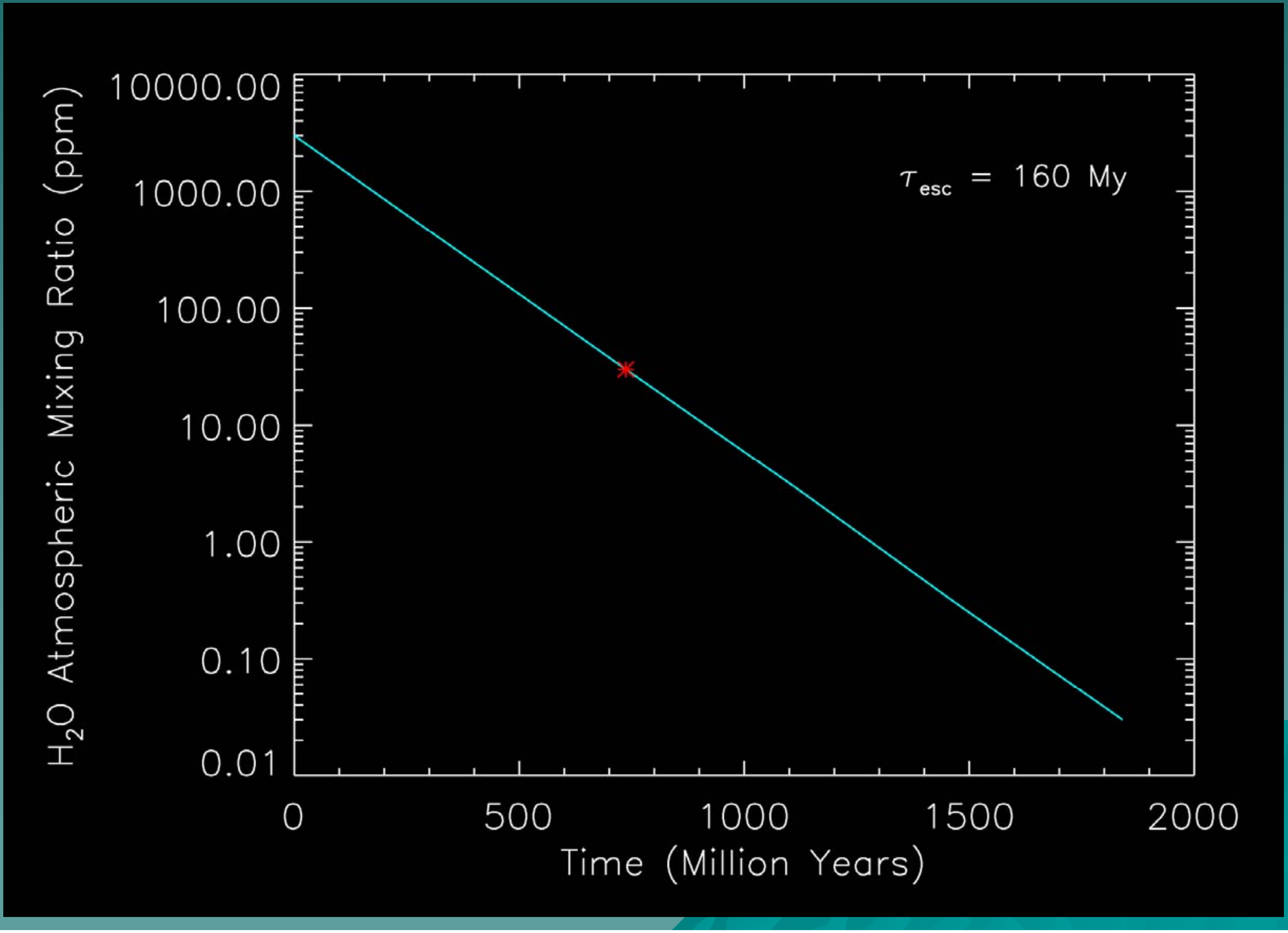
Climate Evolution

- Radiative-Convective Model
- Coupled Cloud Microphysics
- Exospheric Escape of H,D
- Volcanic Outgassing
- Reactions with Surface

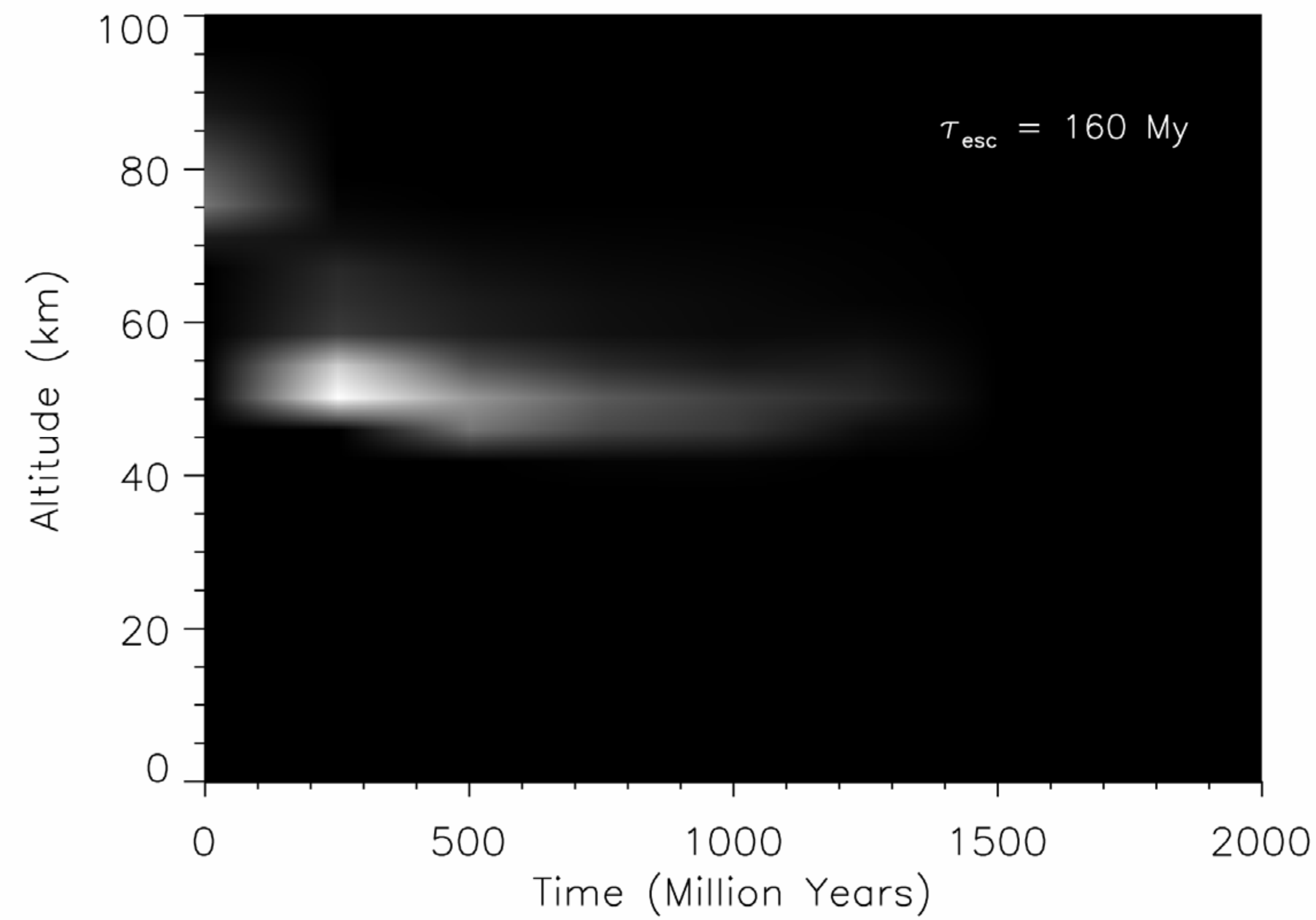
Venus Greenhouse Sensitivity Studies

Source Deleted	Change in Surface Temperature
HCl	1.5 K
CO	3.3 K
SO_2	2.5 K
Clouds	142.8 K
H_2O	68.8 K
OCS	12.0 K
CO_2	422.7 K

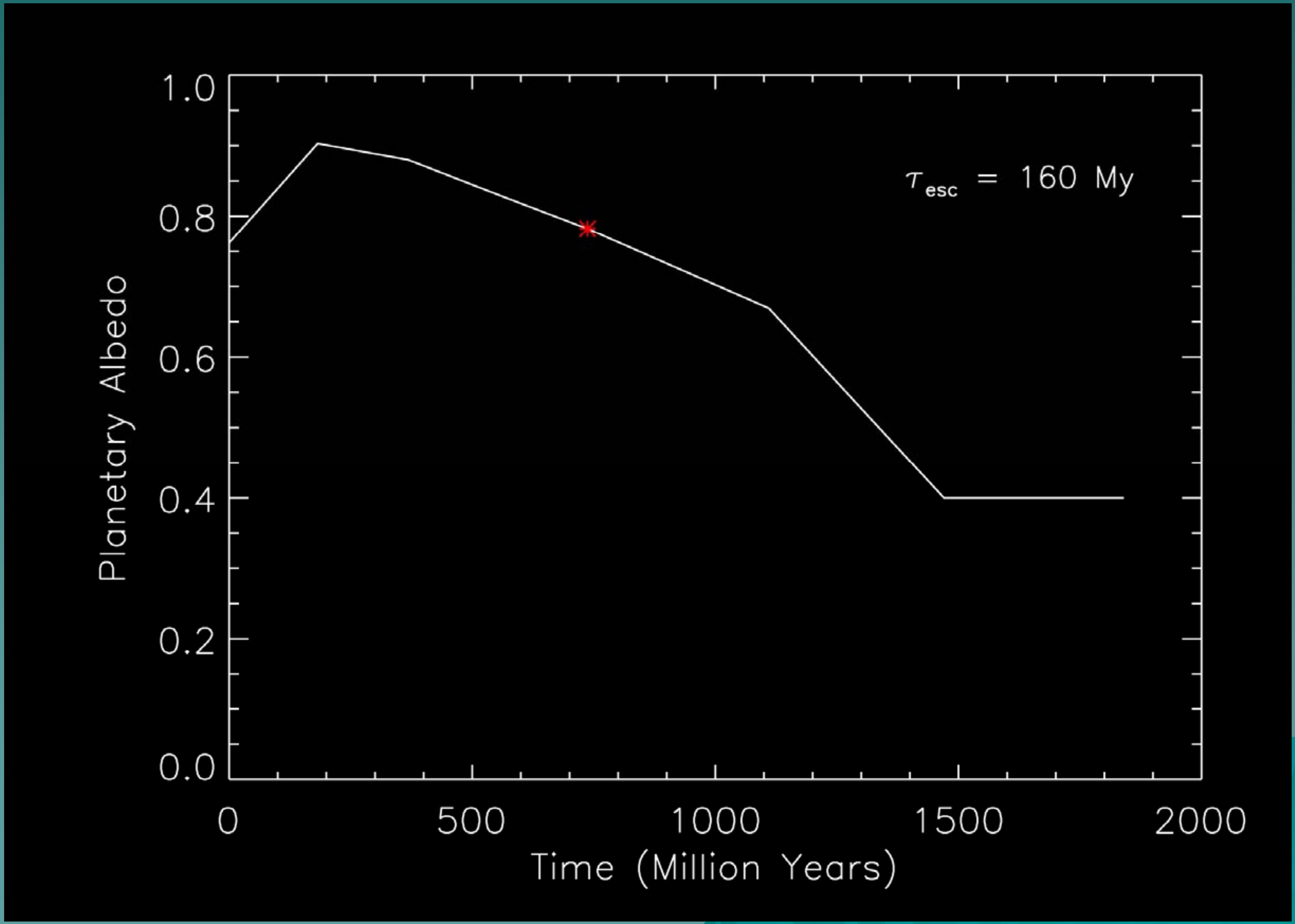
Temperature changes due to H_2O



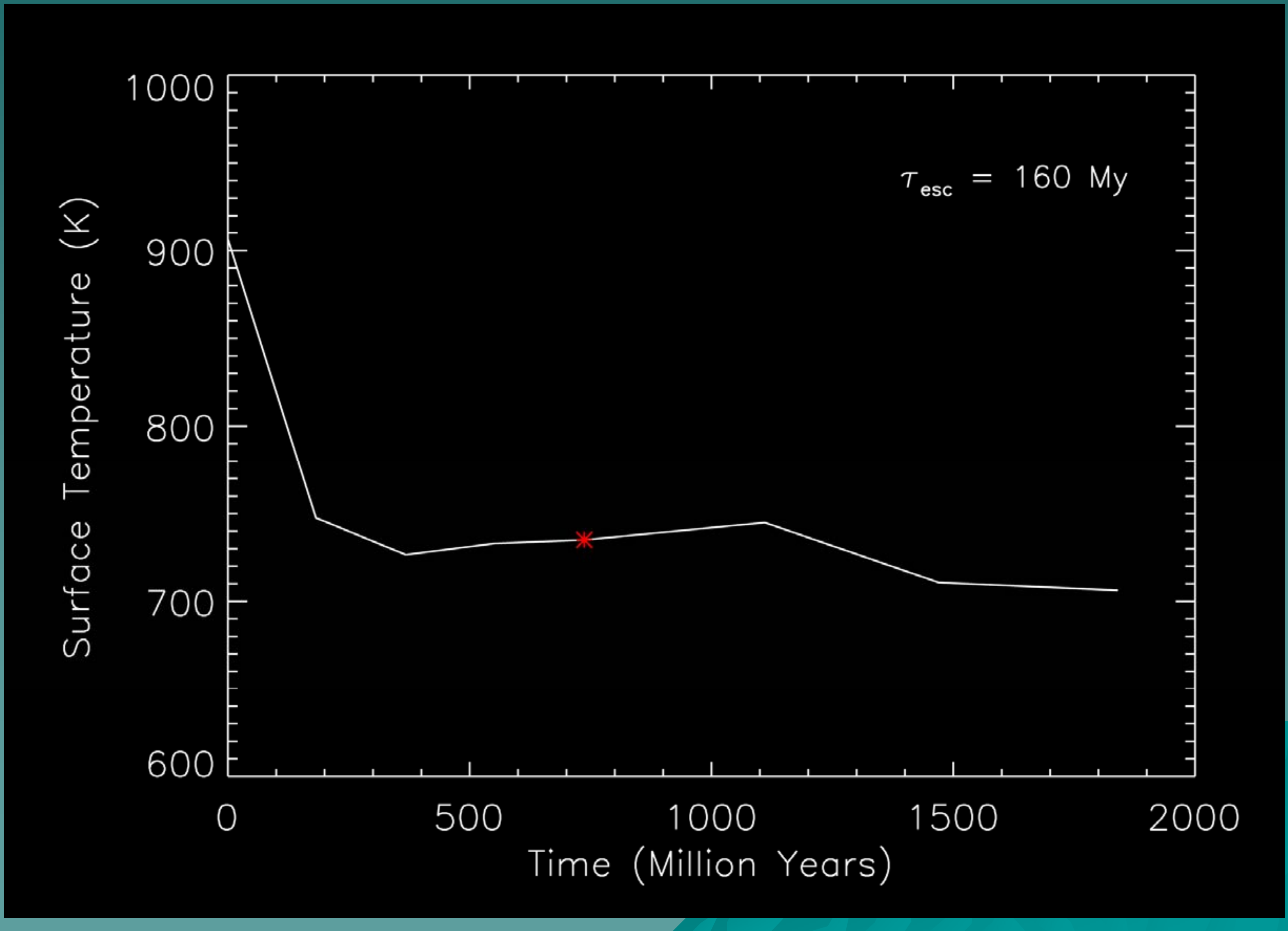
Cloud changes due to H_2O



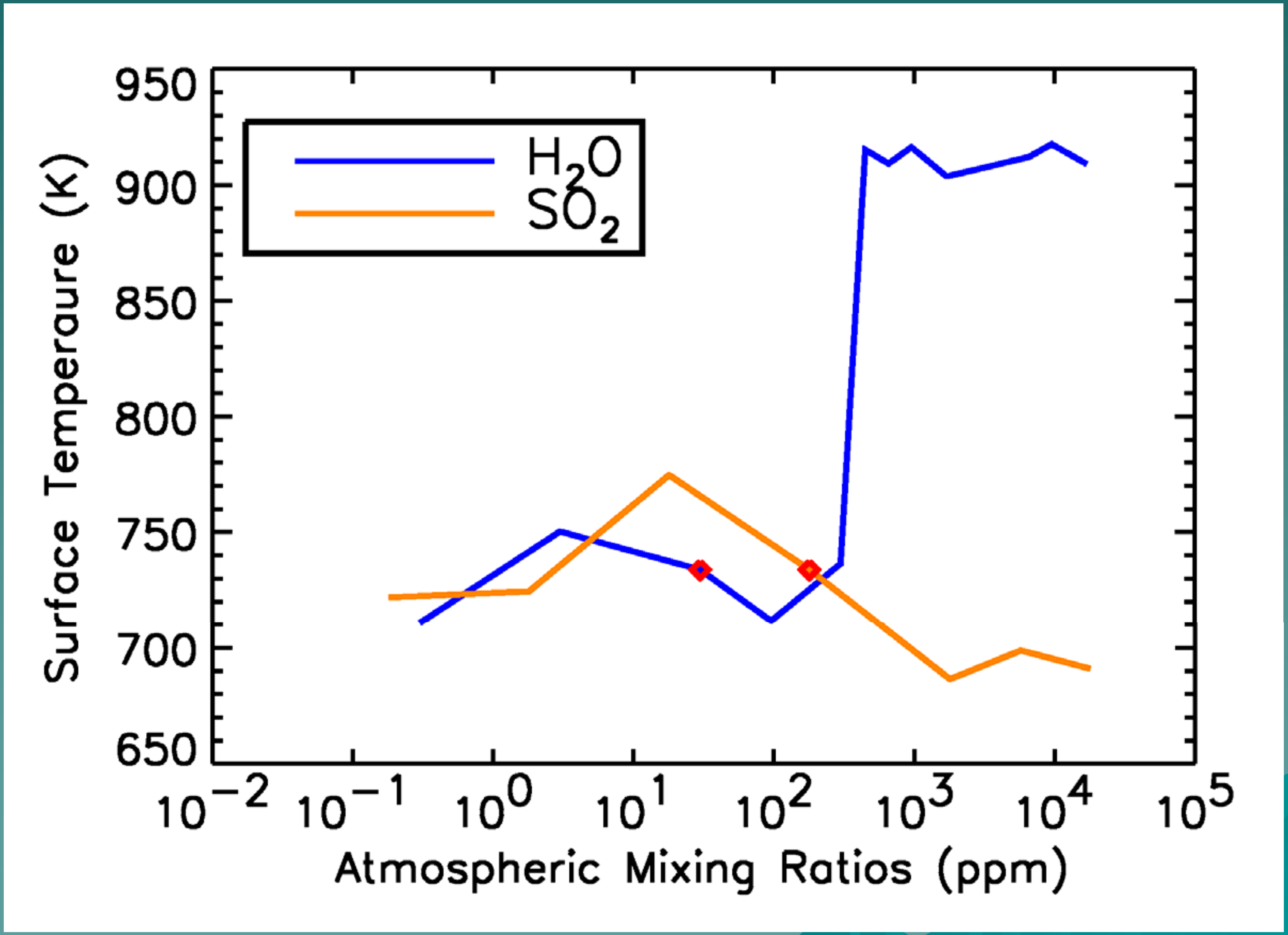
Planetary Albedo Changes due to H_2O



Surface Changes due to H_2O



Venus Thermostats II



Geologic Sulfur Cycle

$2H_2S + 3O_2 \rightarrow 2H_2O + 2SO_2$

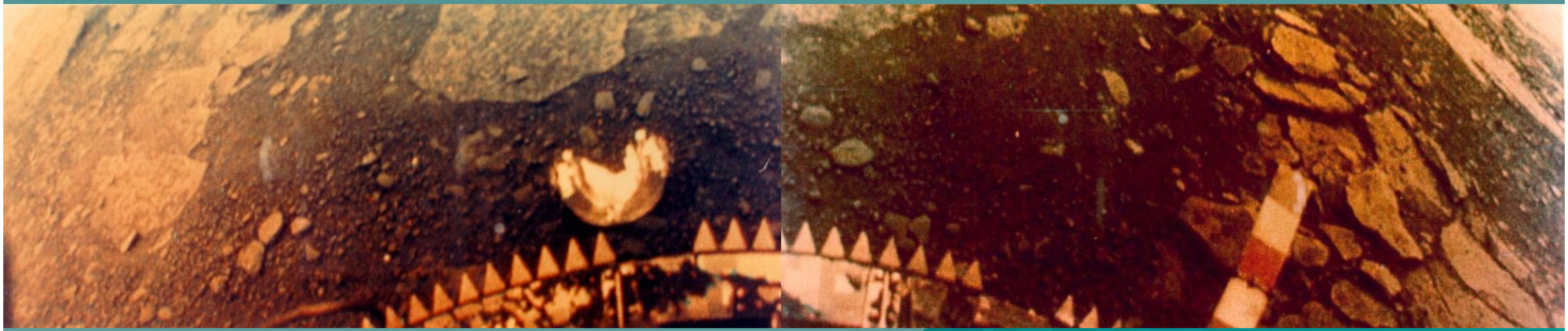
$2COS + 3O_2 \rightarrow 2CO_2 + 2SO_2$

$FeS_2 + 2H_2O \rightarrow$
$FeO + 2H_2S + 1/2O_2$

$FeS_2 + 2CO_2 \rightarrow$
$FeO + 2COS + 1/2O_2$

$SO_2 + 1/2O_2 + CaCO_3 \rightarrow$
$CaSO_4 + CO_2$

$2CaSO_4 + FeO + 2CO_2 \rightarrow$
$FeS_2 + 2CaCO_3 + 7/2O_2$



Sulfur Gas Reactions with Surface

- Fegley and Prinn (1989) showed that SO_2 reacts vigorously with carbonates under Venus conditions.
- Currently, SO_2 is 100X more abundant in Venus atmosphere than it would be if it were in equilibrium (caveat: Vega).
- Climate models show that this excess atmosphere should react with the surface in ~30 My and the clouds would disappear.
- SO_2 measurements in the lowest scale height are extremely important!

Temperature-Dependent Geochronometers

- Most amphiboles and micas are not thermodynamically stable on Venus (Zolotov *et al.* 1997).
- However, tremolite is metastable, decaying over timescale of ~1 By (Johnson and Fegley 2000).
- Large temperature difference between highlands and lowlands of Venus means that differential decay of amphiboles will occur.

Differential Tremolite Abundance

Rate Law for Decomposition

$$k = Ae^{-\frac{T_a}{T}}$$

Adiabatic Atmospheric Lapse Rate

$$T(z) = T_g - \Gamma z$$

Rate of Change of Concentration

$$\frac{dX(z,t)}{dt} = -Ae^{-\frac{T_a}{T(z)}}$$

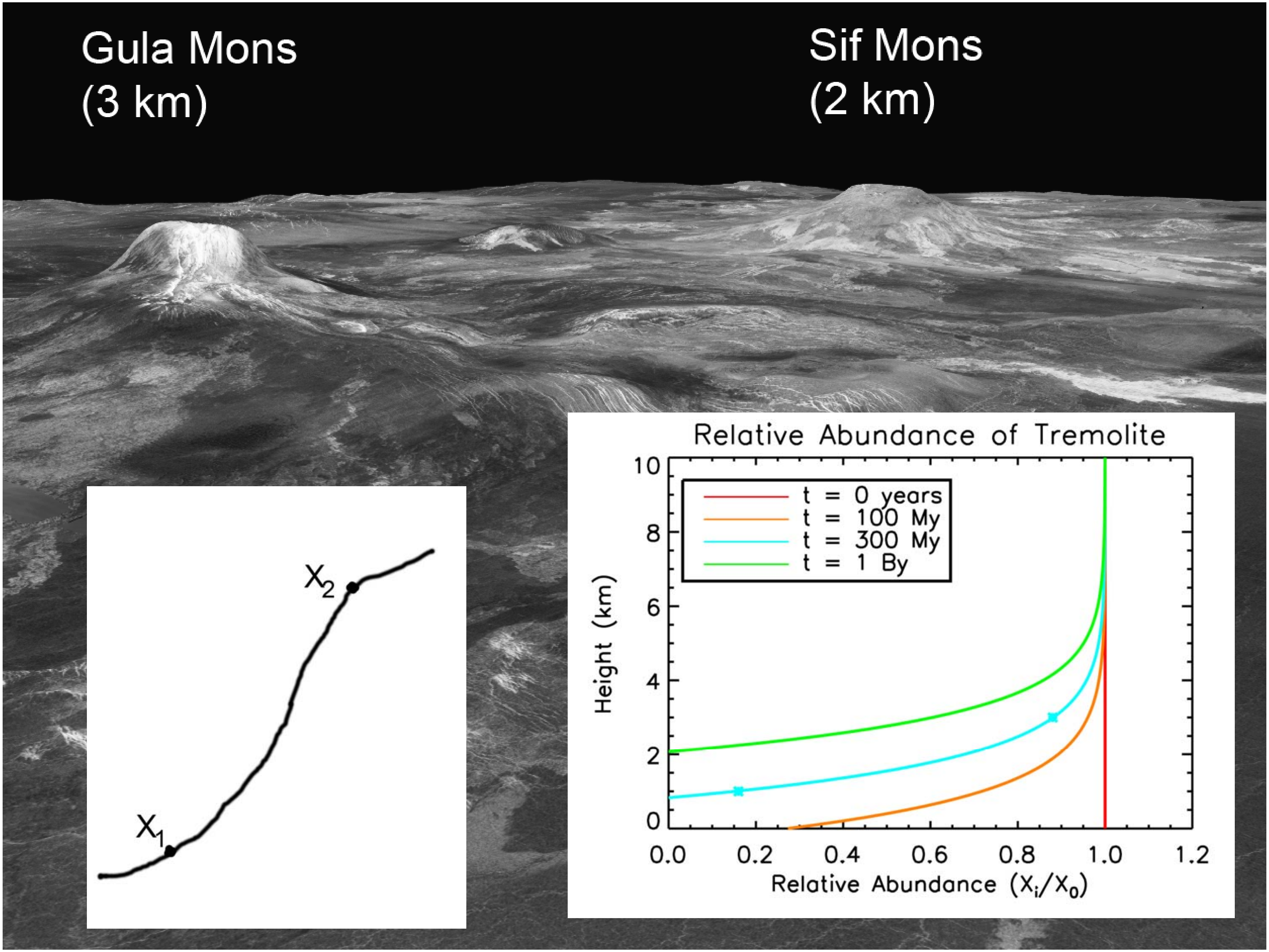
Surface Age Determination

Integrate

$$X(z,t) = X_o(z) - Ae^{-\frac{T_a}{T_g - \Gamma z}}t$$

Average Age

$$t^* = \frac{X(z_2,t^*) - X(z_1,t^*)}{A\left(e^{-\frac{T_a}{T_g - \Gamma z_1}} - e^{-\frac{T_a}{T_g - \Gamma z_2}}\right)}$$


Gula Mons
(3 km)
Sif Mons
(2 km)
X1
X2
Relative Abundance of Tremolite
t = 0 years
t = 100 My
t = 300 My
t = 1 By
Height (km)
Relative Abundance (Xi/X0)
0
2
4
6
8
10
0.0
0.2
0.4
0.6
0.8
1.0
1.2

Conclusions

- Accurate (ppb) measurements of Ne, Ar, Kr, Xe, and N atmospheric isotopes are crucial for understanding the early evolution of Venus' atmosphere.
- Theoretically, it is easy to perturb Venus' atmospheric and surface temperatures.
- Existence of clouds today implies volcanism active in the last 30 My.
- SO_2 measurements in the lowest scale height are of utmost importance, as are sulfate, Fe, and carbonate mineralogy.
- *In situ* mineralogy of hydrated minerals may provide important clues to the age of surface units and/or temperature changes.