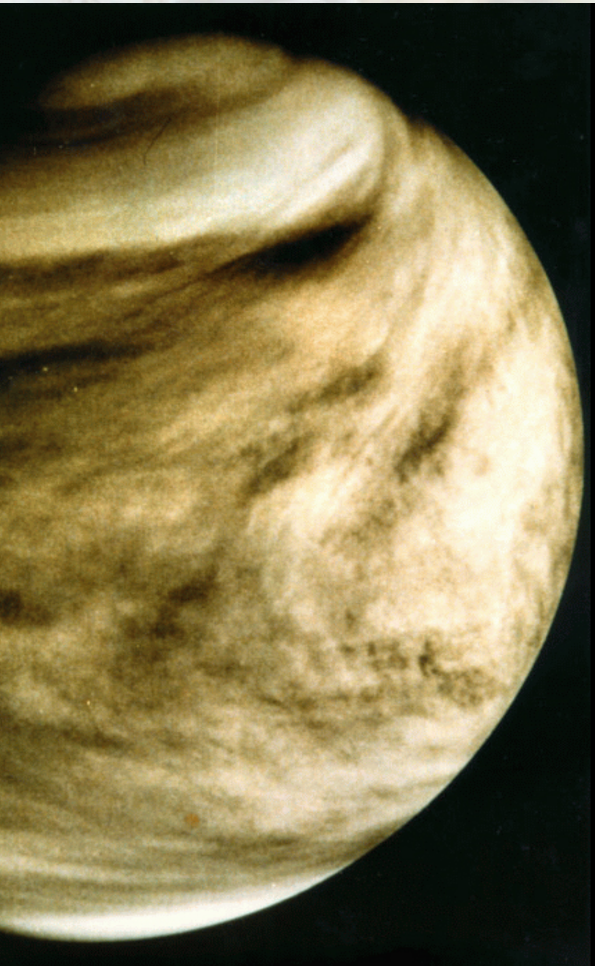
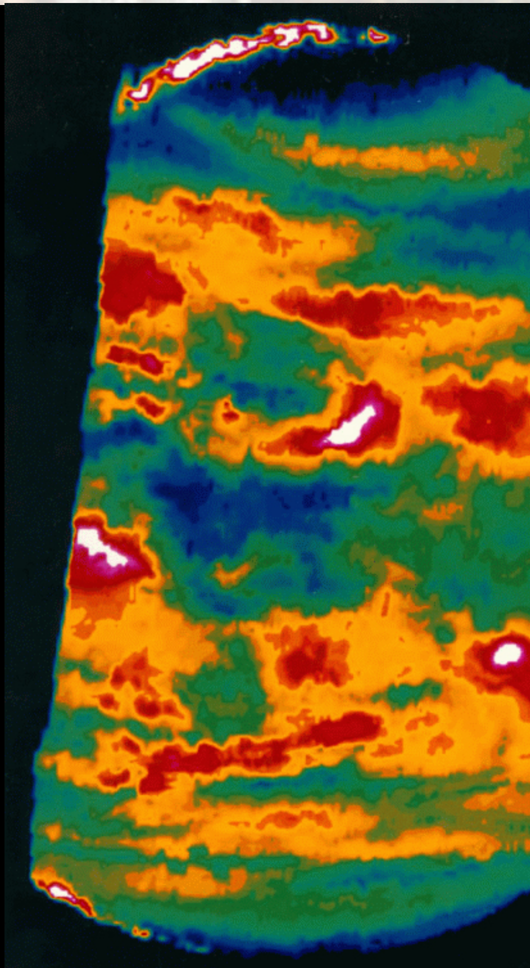
Evolution of the Atmosphere and Climate of Venus





David Grinspoon
Planetary Science Institute

EPSC 2014, Cascais

Evolution of the Atmosphere and Climate of Venus

David Grinspoon, Mark Bullock, Kevin Zahnle, Helmut Lammer

Introduction (DG)

The divergent evolution of Venus and Earth.
What is new since Venus II book – Venus Express, Ground-based, New models, Exoplanets.

Accretion & Primordial Atmosphere (KZ)

What is known and what is surmised about accretion.
The first atmosphere.
Rare gas clues.

Atmospheric Loss over Time (HL & DG)

Was there ever an ocean?
Hydrodynamic escape
Nonthermal escape
Constraints from Venus Express

Climate History (MB & DG)

Runaway and Moist Greenhouse
Coupled Surface/Climate Evolution
Climate Feedbacks Today
Venus and the Future of Earth's Climate

Future Exploration and Atmospheric Evolution (DG)

Crucial measurements for progress, and mission prospects
Venus Atmosphere and Exoplanet Exploration
Mapping habitable zones
False Oxygen positives and early Venus

Conclusions (DG)

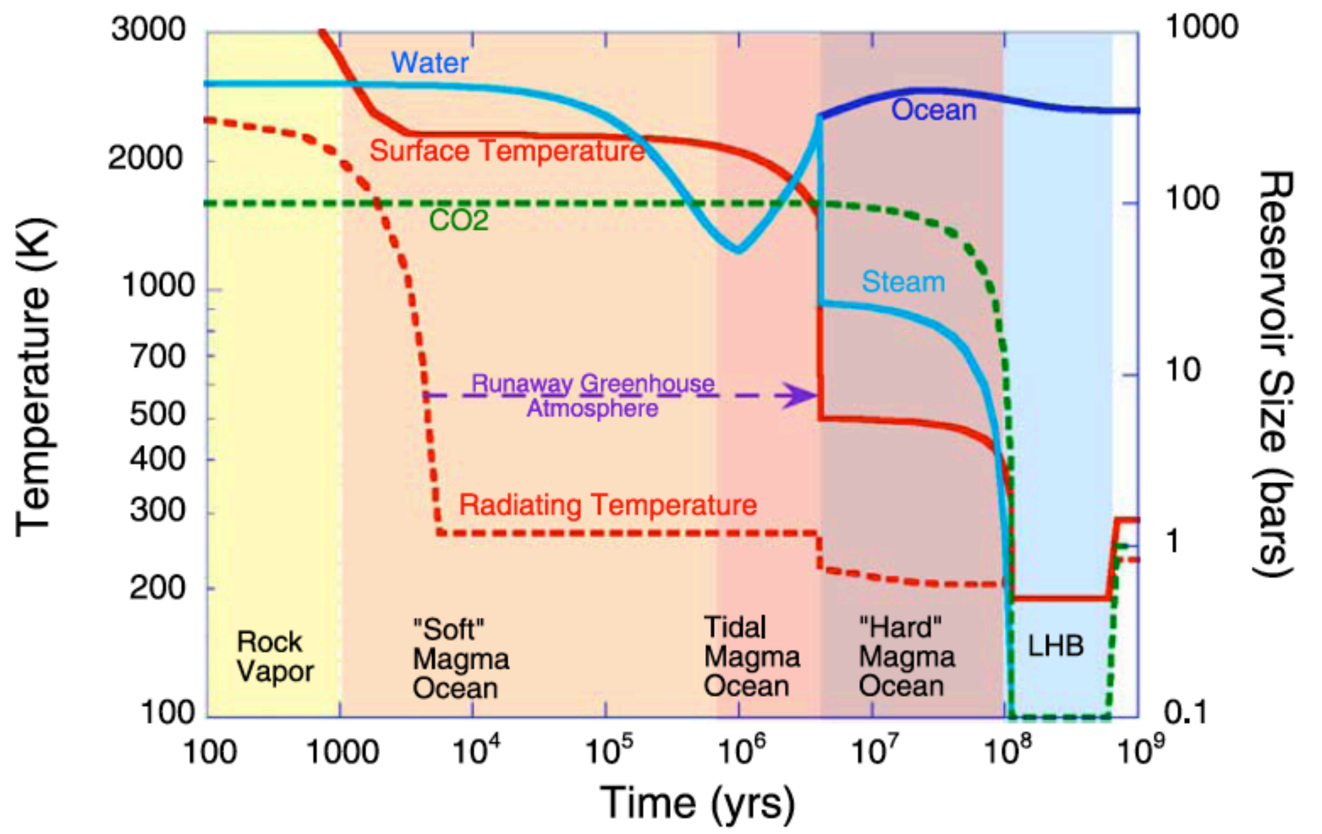
Large Impacts, Magma Oceans, Steam Atmospheres, Hydrodynamic Escape

The young planets existed in a swarm of impacting material.
(So they were all “dwarf planets” according to IAU)

On Earth and Venus (and Mars?) energy from large impacts would have created magma oceans and steam atmospheres. (Matsui & Abe; Zahnle et al., Elkins-Tanton)

The earliest atmospheres were silicate, followed by hot water vapor plus CO_2, CO, H_2.

Zahnle et al. 2007 “Emergence of a Habitable Planet”



Did Venus Have Oceans?

No direct evidence! (a central goal for future missions)

But Venus surely accreted with substantially more water than it has now.
Indirect/circumstantial evidence:

* D/H ratio > 100 x $\oplus$. A large fractionation requires a severely depleted reservoir. Requires that most of the water to have ever resided on the surface or in the atmosphere of Venus has escaped. Does not prove there was ever surface water.

* Formation: Did Venus and Earth accrete with the current factor of 10^5 difference in water abundance? No formation model predicts, or can account for, this extreme segregation. Nature is not that neat and tidy and not prone to huge, random decreases in entropy. "Occam's razor": Venus formed with orders more water.

* Almost surely all terrestrial planets formed quite wet (Matsui & Abe, Zahnle, Elkins-Tanton, etc.

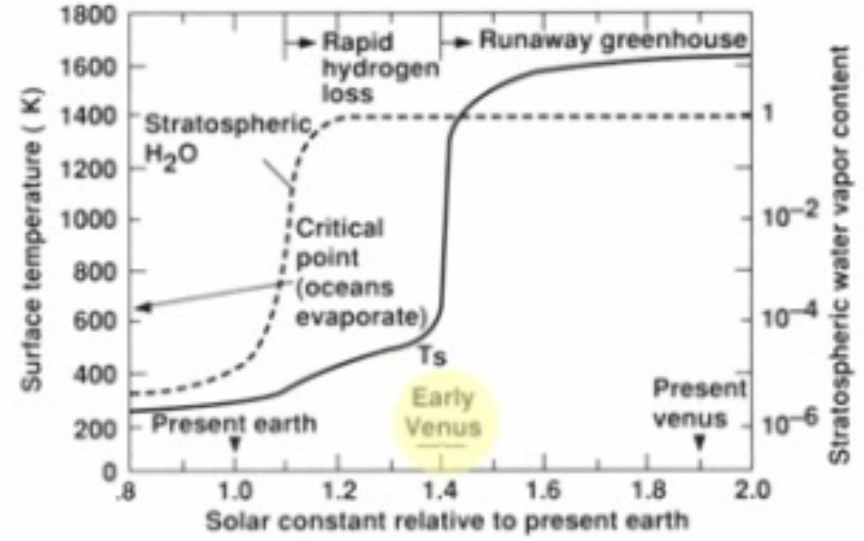
* Climate models: with faint young Sun: water would be liquid. (but depends on unknown albedo & cloud/radiation interactions)

However, early solar activity may have prevented surface water condensation and removed most hydrogen and water.

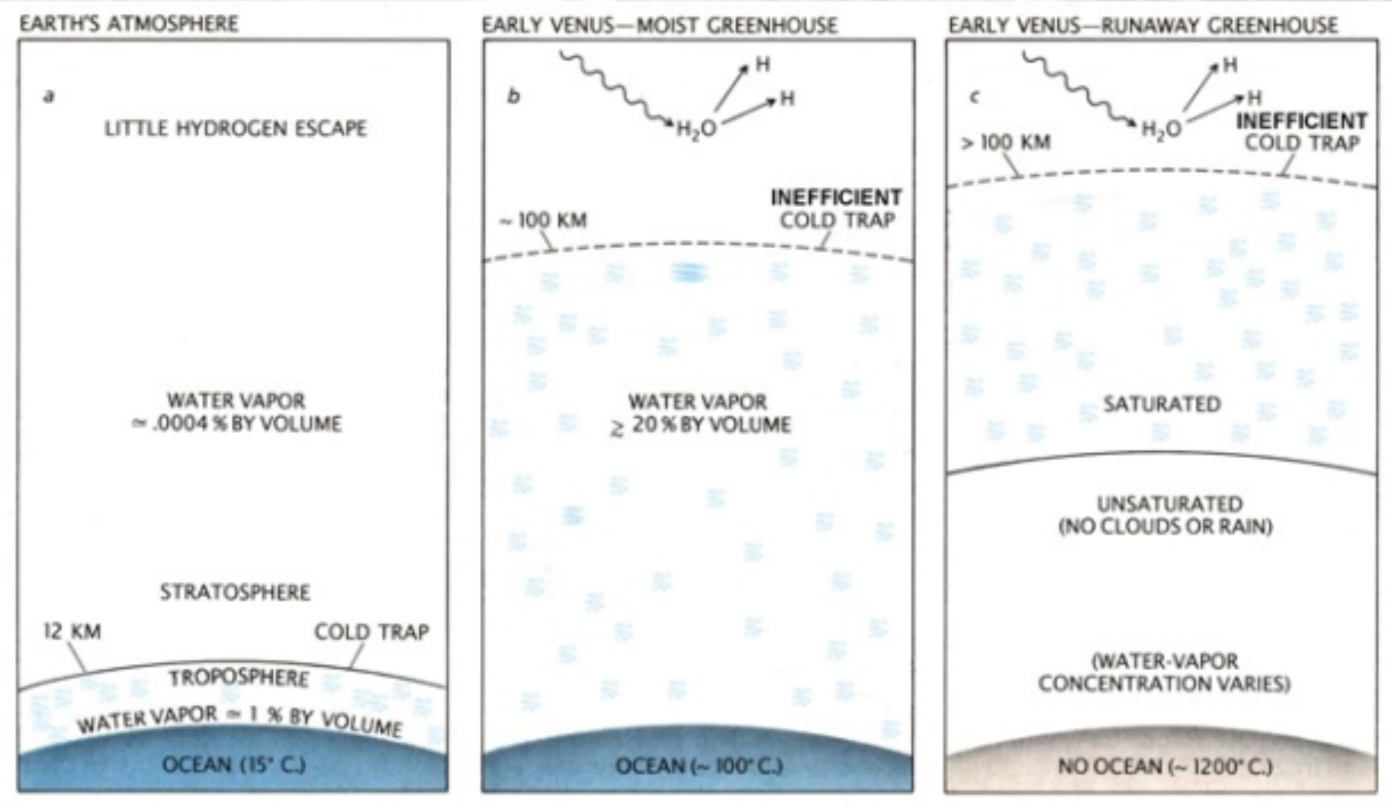
The Faint Young Sun and Early Venus:

S ≈ 1.4 x present Earth.

This is right on the edge of a runaway condition.



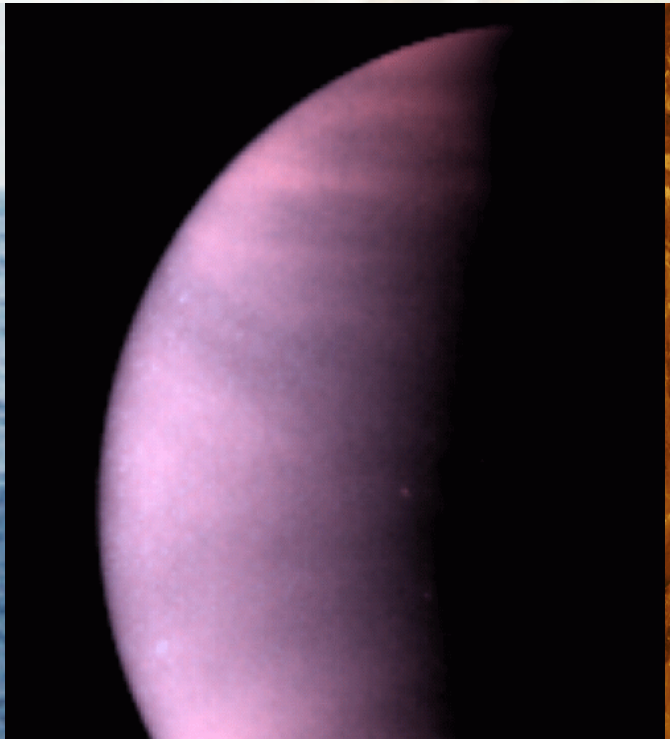
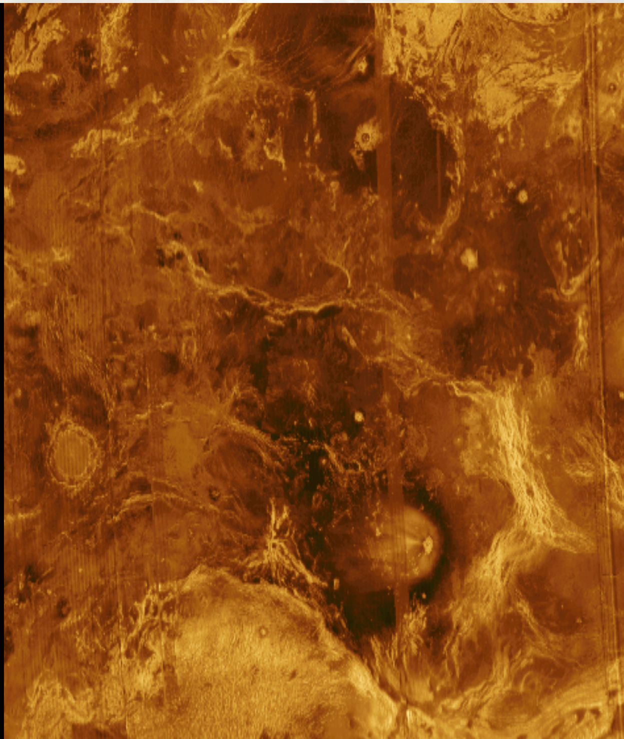
Venus can have warm oceans and a “moist greenhouse”



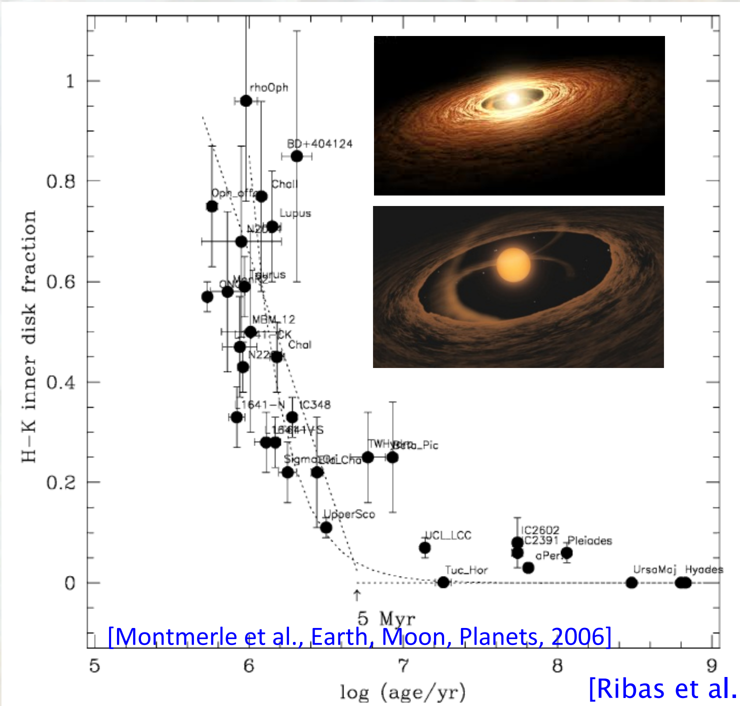
Uncertainties in longevity of an early Venus ocean are very large.

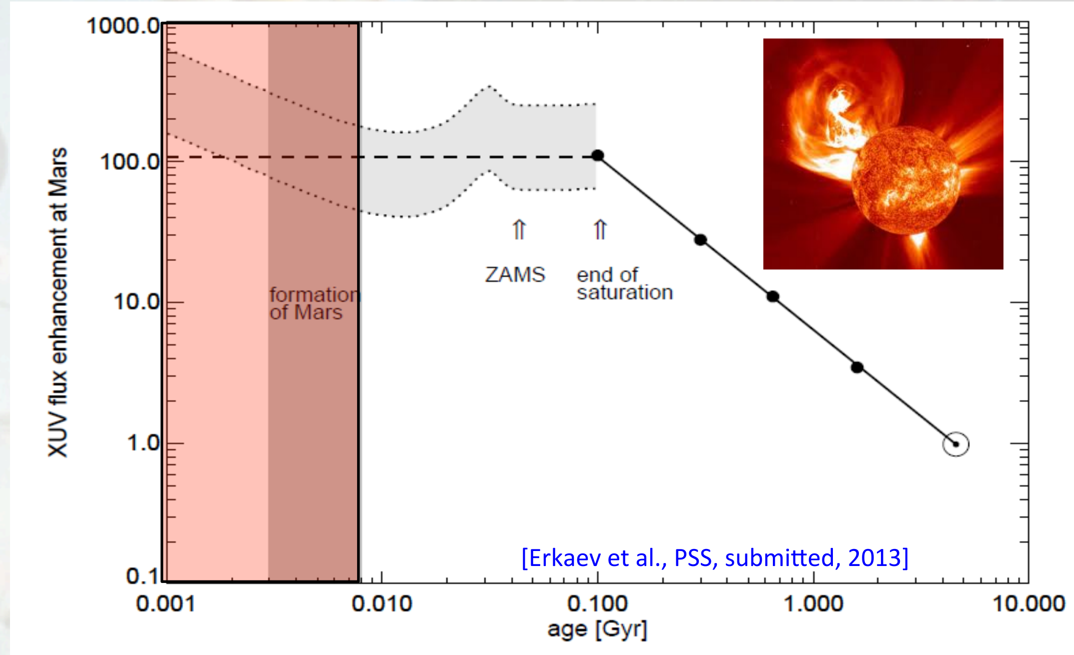
- **Clouds excluded from published models**.
- No cloud feedback which, qualitatively, is expected to stabilize surface temperatures against rising solar flux, and therefore extend the lifetime of the moist greenhouse.

- Cloud feedback may have extended the longevity of Venus oceans to 2 GY (Grinspoon & Bullock, 2007)

The young Sun's (G-star) radiation environment and nebula life time



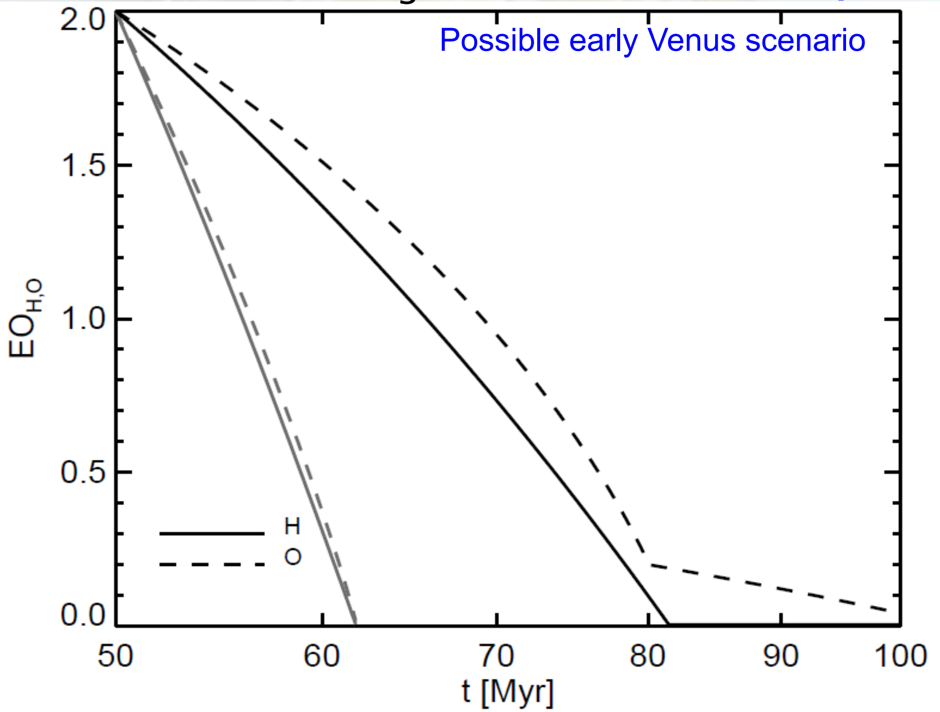


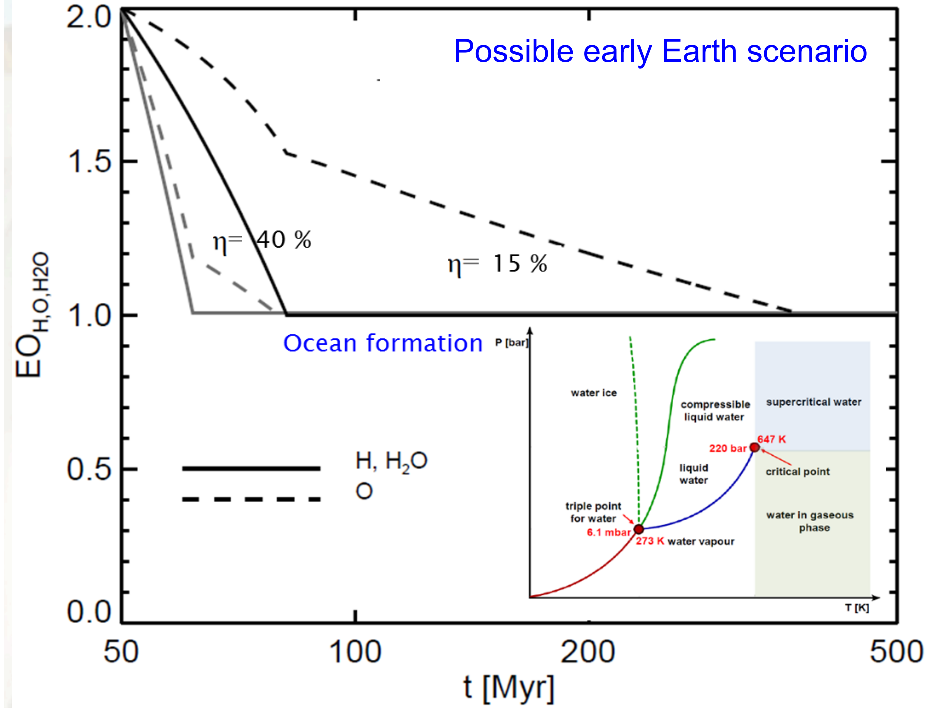
[Ribas et al., ApJ, 2005; Güdel, 2007; Lammer et al., EPS, 2012]

Solar age [Gyr]	t b.p. [Gyr]	X-ray [1–20Å]	SXR [20–100Å]	EUV [100–920Å]	FUV [920–1180Å]	Lyman-α [1200–1300Å]
0.7	3.9	37	11	8.6	5	3.9
0.65	3.95	43	12	9.4	5.3	4.1
0.6	4.0	50	13	10	5.7	4.3
0.55	4.05	59	15	11	6.1	4.6
0.5	4.1	71	17	13	6.6	4.9
0.45	4.15	87	19	14	7.2	5.3
0.4	4.2	109	22	17	8	5.8
0.35	4.25	141	26	19	9	6.4
0.3	4.3	189	32	23	10	7.1
0.25	4.35	268	40	28	12	8.1
0.2	4.4	412	54	37	14	9.6
0.15	4.45	715	77	51	18	11.8
0.1	4.5	1558	129	82	26	15.8

Escape of early Venus` & Earth`s expected outgassed steam atmospheres

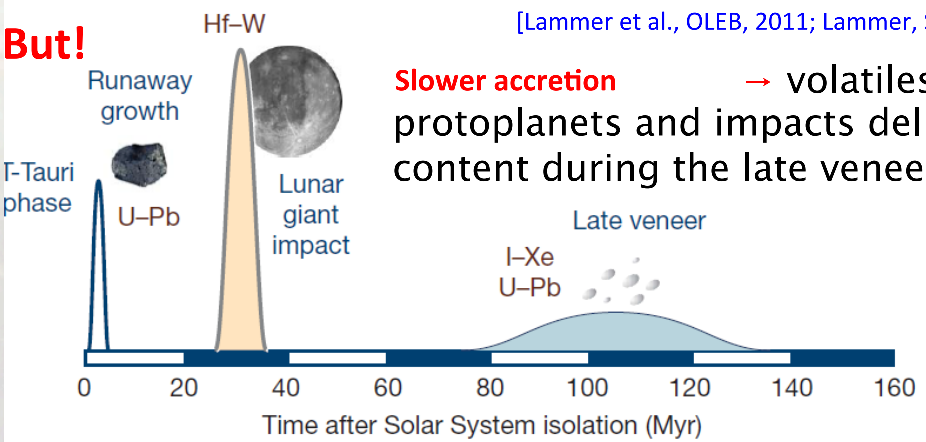
Ocean formation by volatile outgassing → steam atmosphere condenses and forms ocean on Earth but remains in gaseous form on Venus [see also Hamano et al., Nature, 2013]



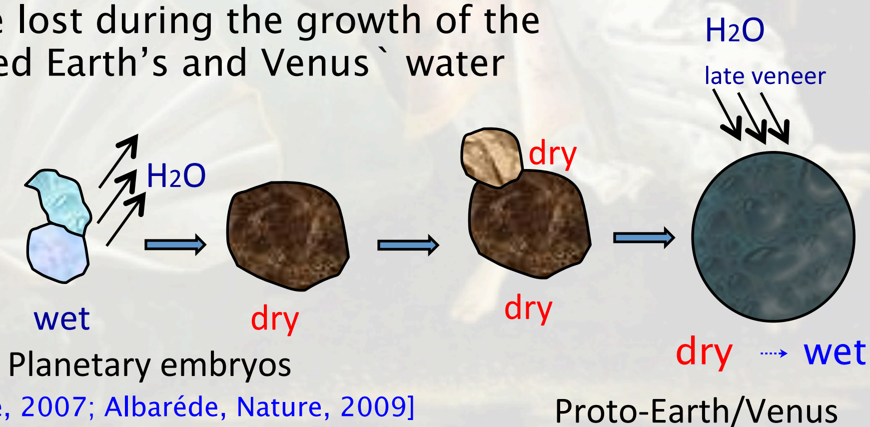


[Lammer et al., OLEB, 2011; Lammer, Springer Briefs in Astronomy, 2013]

But!



Slower accretion → volatiles are lost during the growth of the protoplanets and impacts delivered Earth's and Venus` water content during the late veneer



[Albarède and Blichert-Toft, C. R. Geoscience, 2007; Albaréde, Nature, 2009]

History of Water

Venus – Earth: A divergence but when?

1) Before ocean had chance to condense?

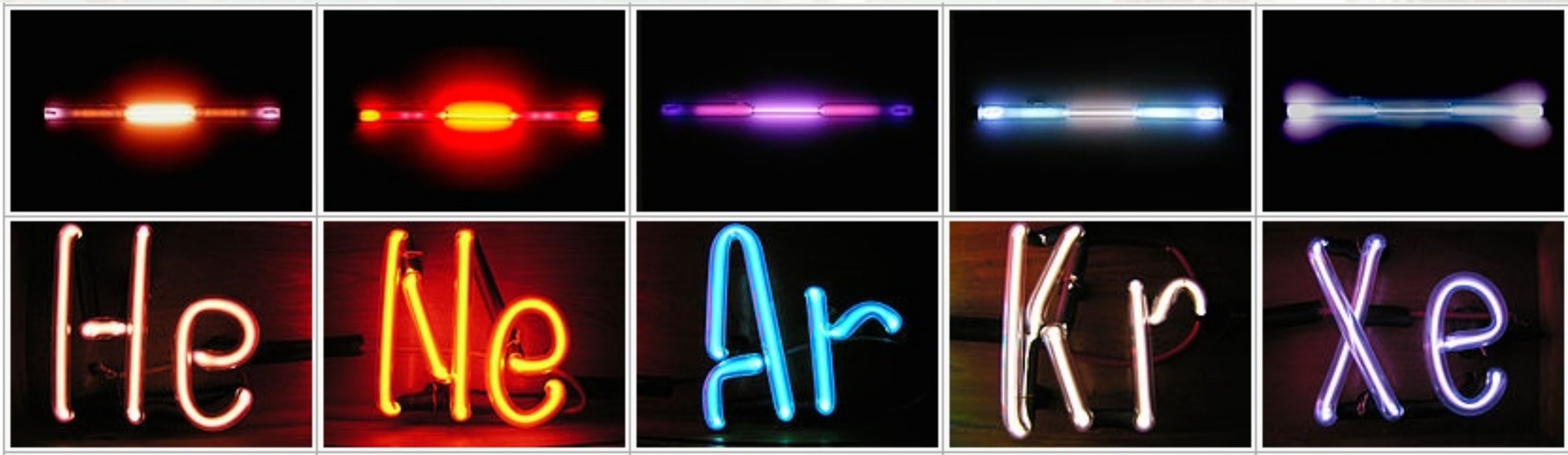
2) Moist greenhouse escape of condensed ocean?

3) On what timescale?

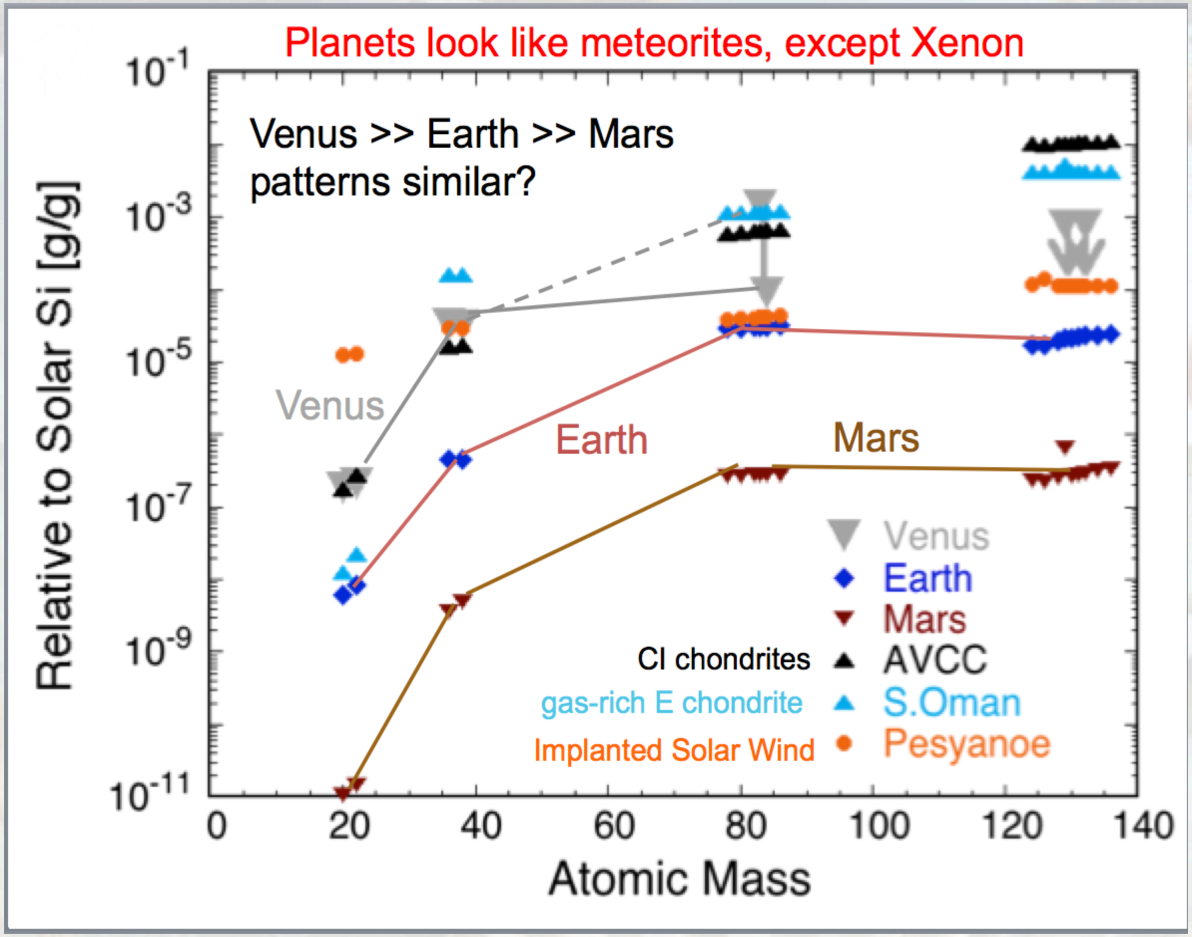
4) Observational tests?
    - Rare gases
    - D/H,
    - Other isotopes? He? Other stable isotopes.
    - Surface composition – Tesserae are Felsic?

Noble Gases

- Simple chemical & physical behavior.
- Major planetary reservoirs accessible in atmosphere (of particular importance for Venus).
- Often imprinted with strong isotopic signatures.
- Rarity makes weak radiogenic signals of mantle or crustal evolution detectable by sampling air.



Pioneer : ^{20}Ne and nonradiogenic ^{36}Ar nearly 100 x > than on Earth!



Contradicted hypothesis that noble gases were tracers for volatiles in general (Anders & Owen, 1977 based on Viking/ Mars)

Late accreting volatile veneer -> Noble gases on Venus should be ≈ Earth.?

Neon and argon 30-70 x more abundant on Venus.

Nearly as rich as in the most gas-rich meteorites.

Suggests differences in Venus & Earth composition, or evolution:

Not yet possible to tell if Venus composition reflects solar wind, enstatite chondrites, carbonaceous chondrites, Earth & Mars, or none of these.

Venus has suffered very little atmospheric escape compared to Earth?

$H_2O_{VENUS} = 10^{-5} \times H_2O_{EARTH}$

$(D/H)_{VENUS} = 120 \pm 40 \times (D/H)_{EARTH}$ (Bezard et al, 2007)

Due to fractionating escape.

But when?

And how much was lost?

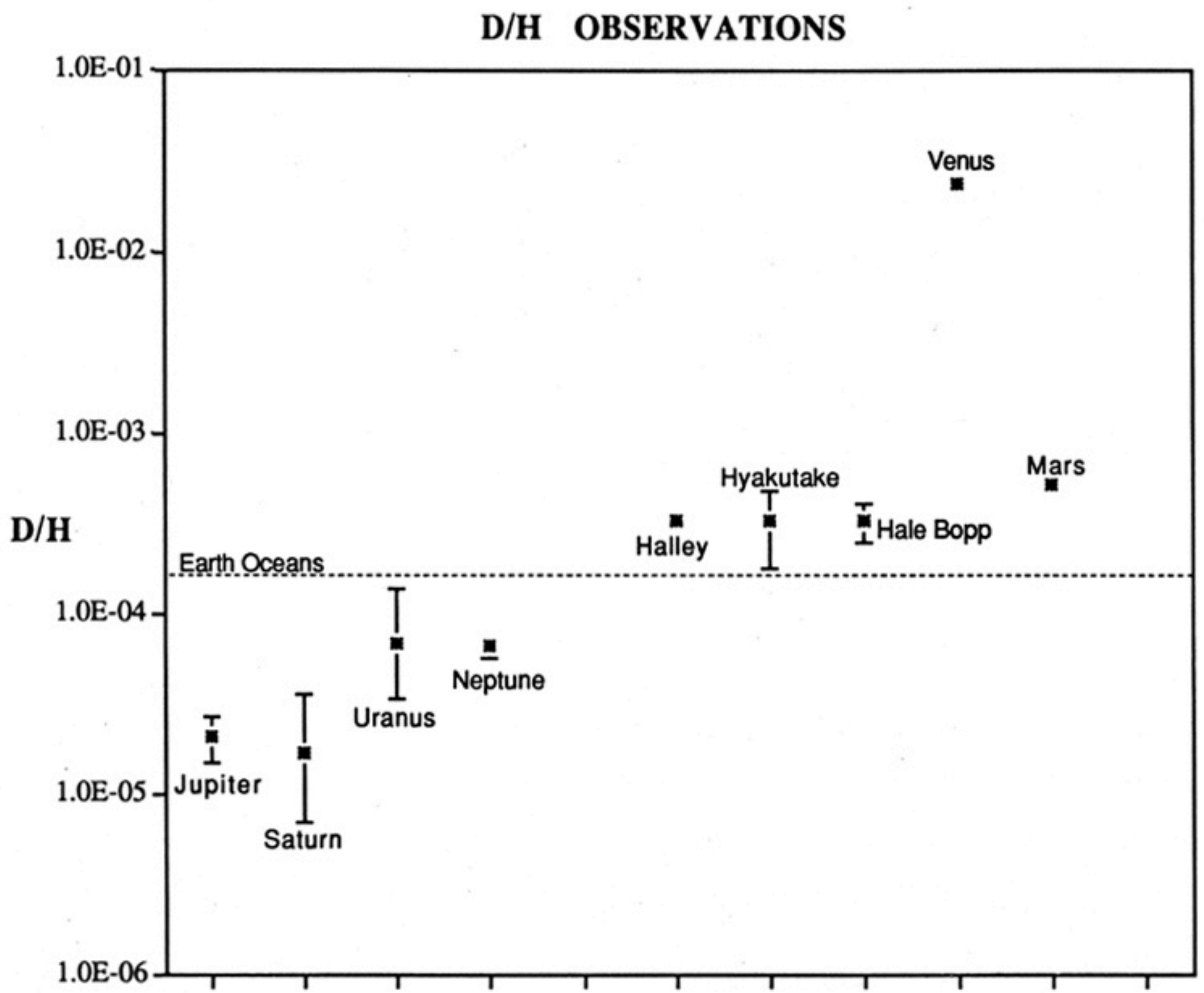
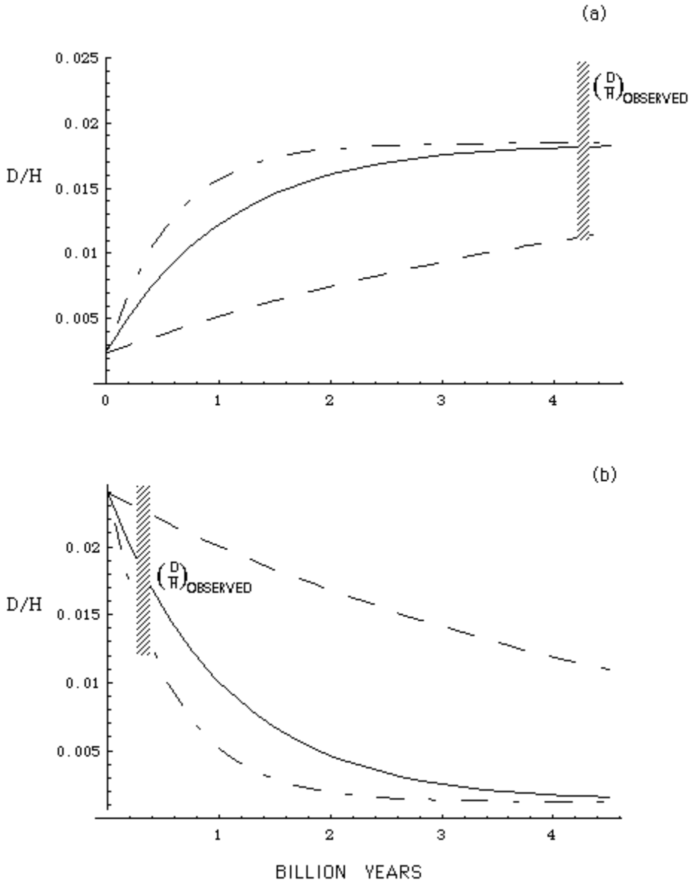


FIGURE 1. STEADY-STATE D/H EVOLUTION.



Implications of the high D/H ratio for the sources of water in Venus' atmosphere

David Harry Grinspoon

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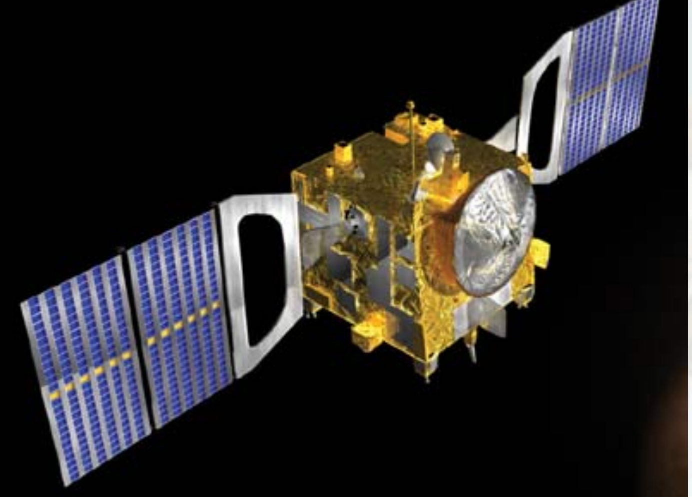
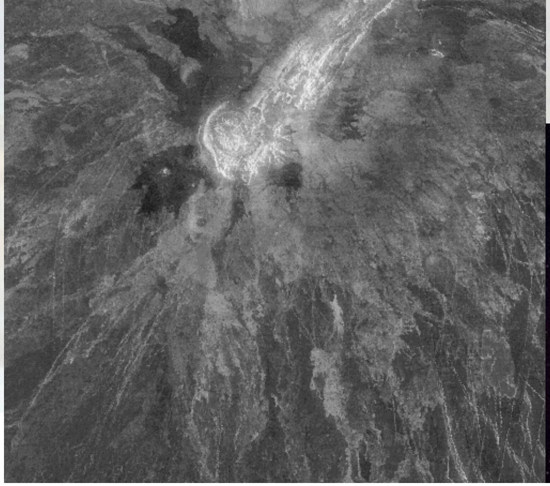
THE high abundance ratio of deuterium to hydrogen in the atmosphere of Venus (120 times that on Earth) can be interpreted either as the signature of a lost primordial ocean[1], or of a steady state in which water is continuously supplied to the surface of Venus by comets or volcanic outgassing, balancing loss through hydrogen escape[2,3]. New observations[4–6] of a water concentration of only 30 parts per million in Venus' atmosphere imply that the residence time of water in the atmosphere, before it escapes to space, is short compared with the age of the Solar System, casting doubt on the primordial ocean hypothesis. But a recent theoretical reanalysis of collisional ejection[7] has increased estimates of the deuterium escape efficiency by a factor of 10: this means that if the venusian water budget is in steady state, the D/H ratio of the source water must be 10–15 times higher than that on Earth, ruling out cometary water, whose D/H ratio is thought to be lower than this[8]. Here I suggest that these observations can be understood either as the result of continuous outgassing from a highly fractionated mantle source (such as might result from severe dessication of the mantle, or massive hydrogen escape early in the planet's history) or Rayleigh fractionation after massive outgassing from catastrophic resurfacing of the planet in the past 0.5–1 Gyr.

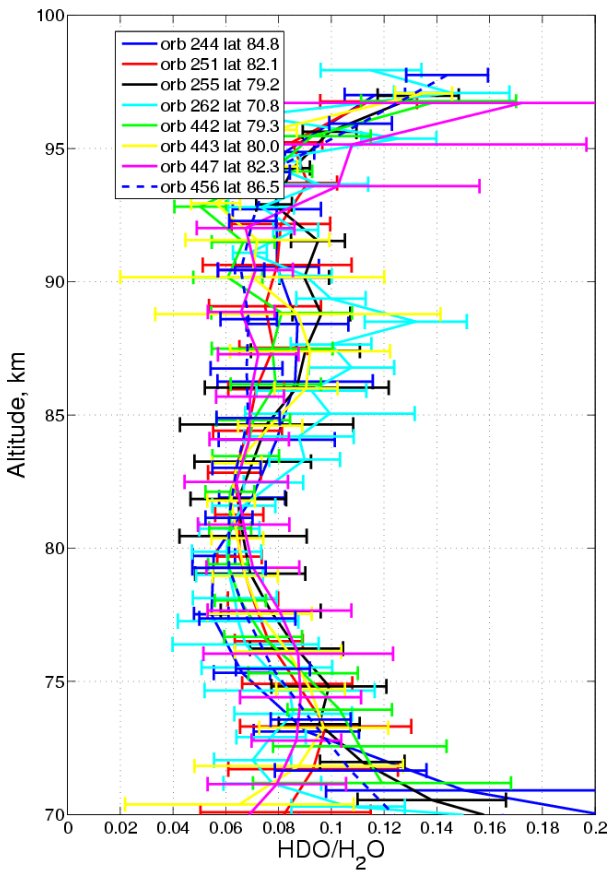
NATURE · VOL 363 · 3 JUNE 1993

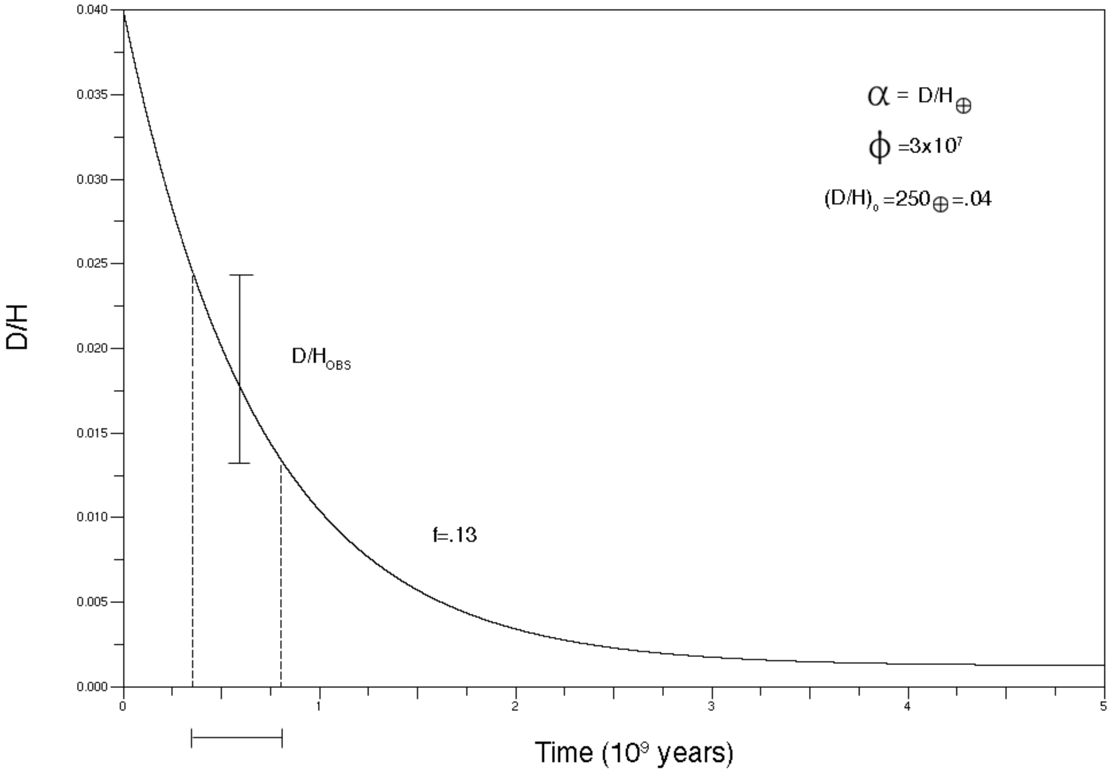
Observed D/H not "primordial residue"; reflects fractionation in the last 1 G.Y.
(Grinspoon, 1993, Donahue 1999)

Escape flux of H, combined with post-Magellan estimates of resurfacing rate allows estimate of magma water content ≈ 50 ppm H_2O. (Grinspoon, 1993)





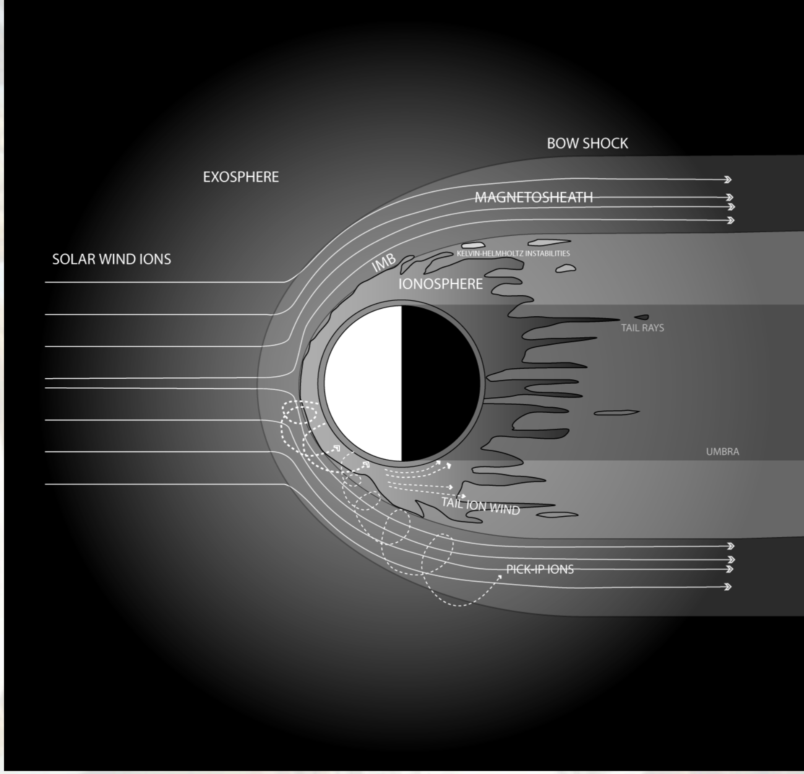




Presently, the problem is underdetermined.
Grinspoon (1993) Taylor and Grinspoon (2010)

ASPERA

Escape of H+ occurs mostly through the plasma wake. With a flux of 7.1×10^{24} s^{-1} . (Federov, Barabash et al. 2008, 2011)



column escape flux of 1.5×10^{6} cm^{-2} s^{-1}

Does this represent the time averaged Hydrogen escape flux? (Escape of neutrals? Low energies? Solar cycle variations?)

An order of magnitude lower than fluxes commonly assumed in evolutionary models!

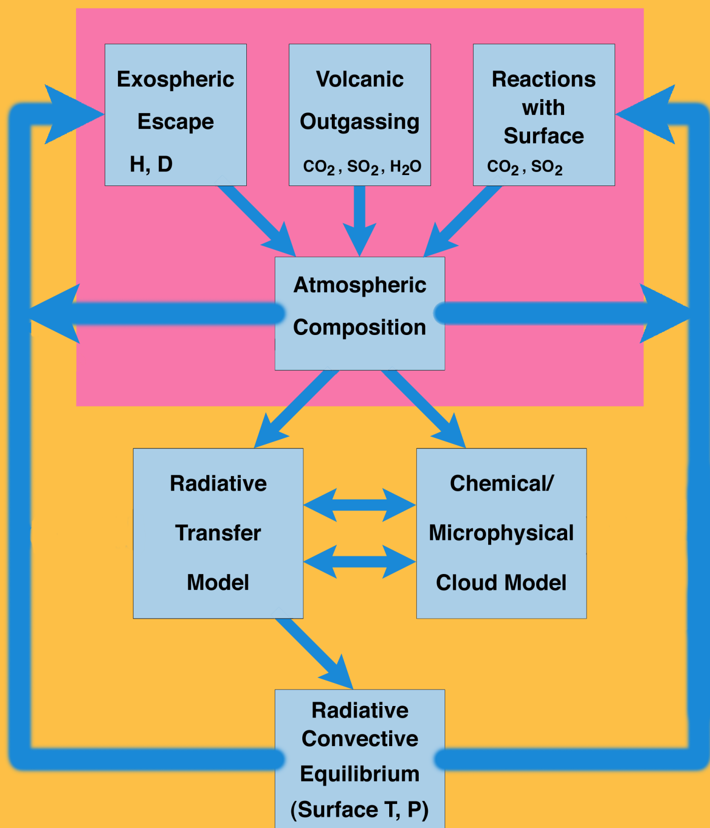
Implies $T_{H2O} \approx 1$ GY (roughly $\approx T_{surface}$!)

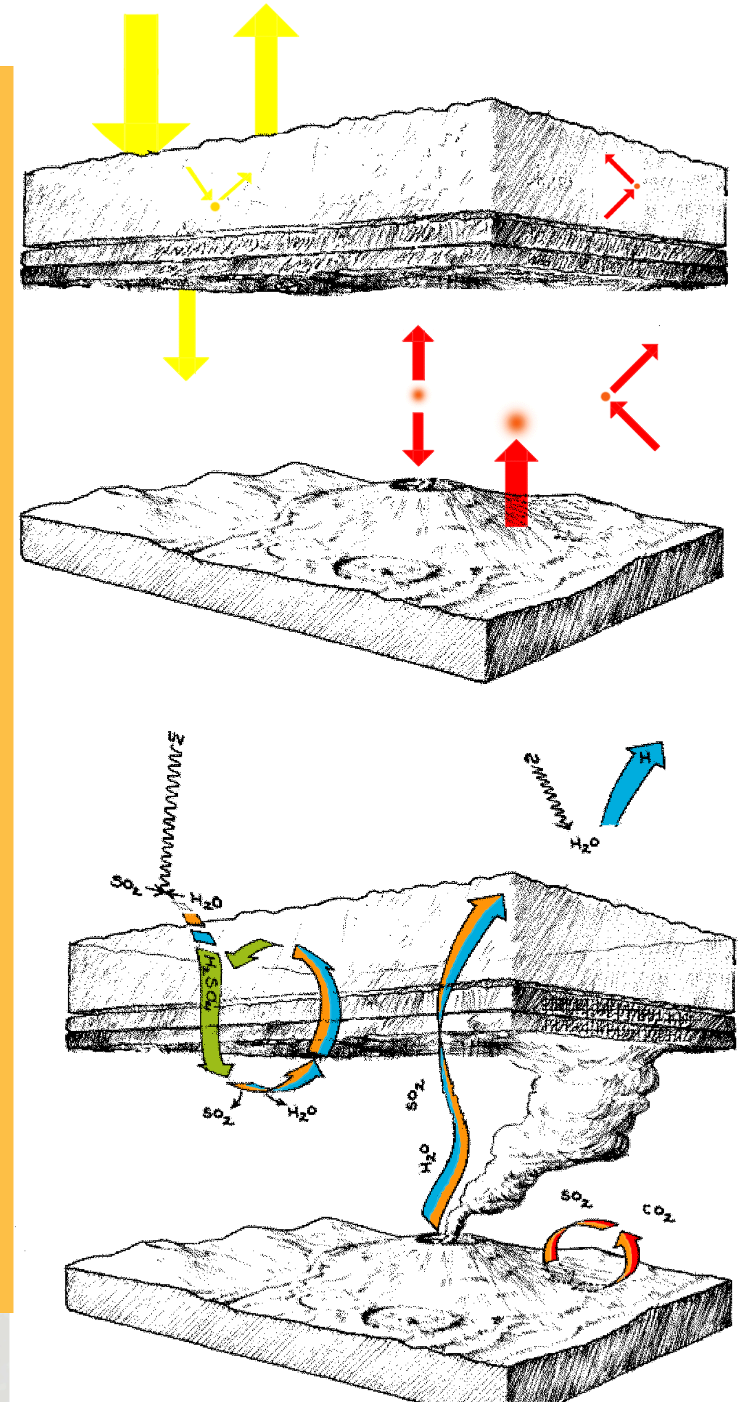
If in steady state with outgassing from post-plains volcanism,
Implies that magmas are very dry! ≈ 5 ppm by mass.
(2 orders of magnitude drier than driest terrestrial magmas!)

The Physics of Venus' Climate

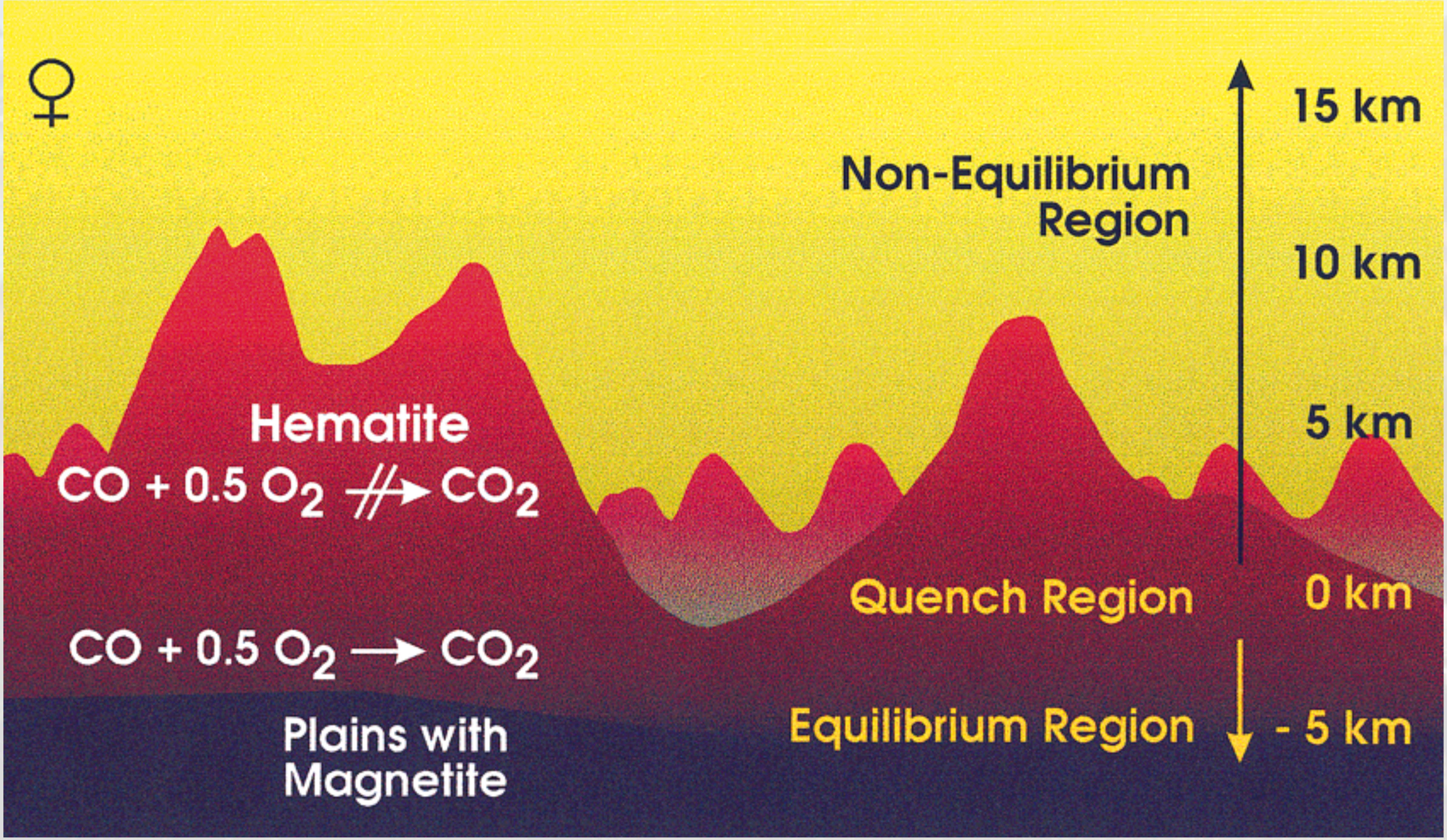
- Solar forcing
- Greenhouse effect – CO_2 Physics
- Greenhouse effect – other gases, clouds, Rayleigh
  - Direct cloud forcing
  - Indirect cloud forcing
- Atmospheric chemistry and clouds
- Cloud microphysics
- Atmospheric dynamics
  - Angular momentum transfer with surface
- Cloud-Radiative Feedback
- Sensitivity of climate to perturbations

Venus Climate Model





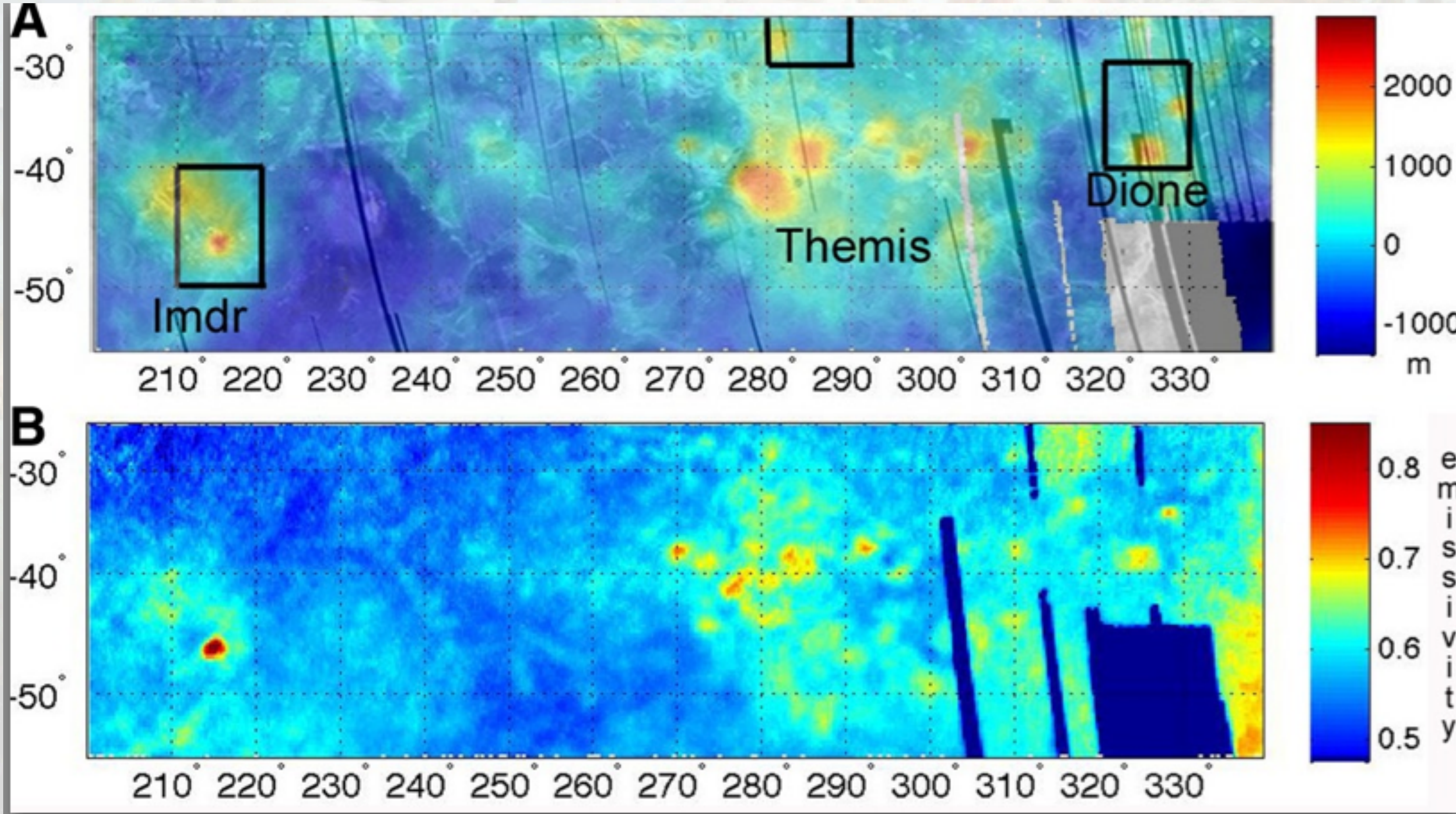
Surface-Atmosphere Chemistry



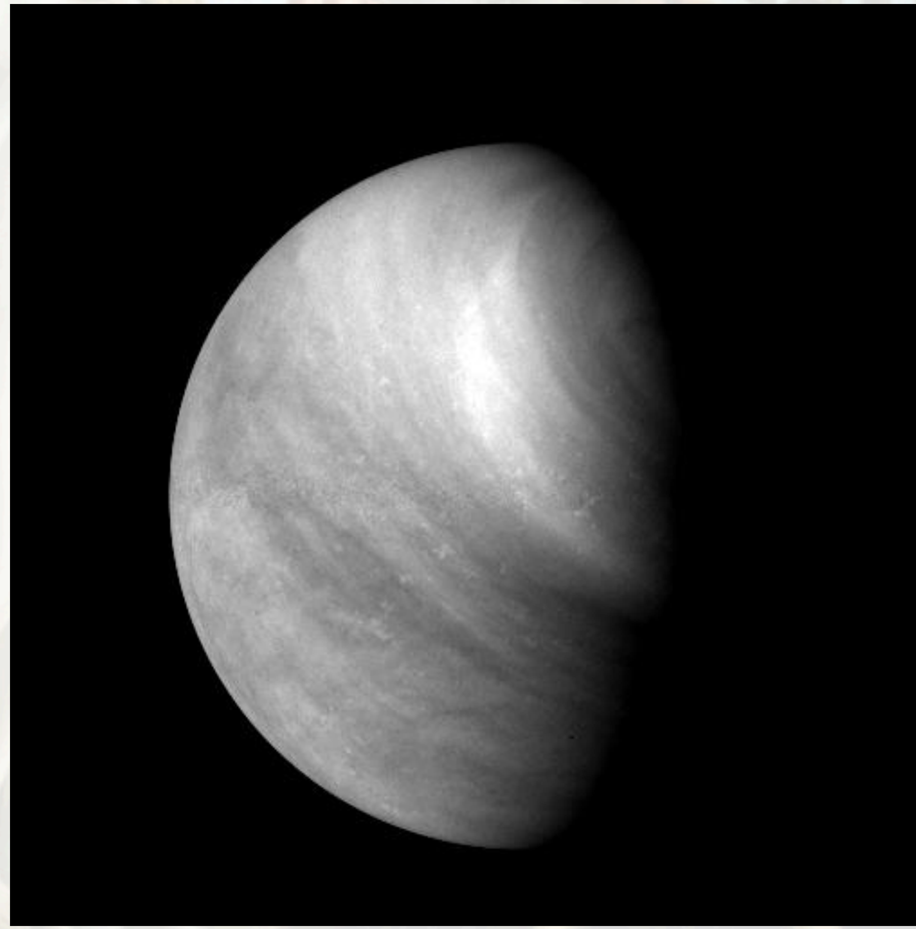
Sciencexpress Report

Recent Hot-Spot Volcanism on Venus from VIRTIS Emissivity Data

Suzanne E. Smrekar,[1]* Ellen R. Stofan,[2] Nils Mueller,[3,6] Allan Treiman,[4] Linda Elkins-Tanton,[5] Joern Helbert[6]



Venus and the Future of Earth’s Climate



ON THE FREQUENCY OF POTENTIAL VENUS ANALOGS FROM KEPLER DATA

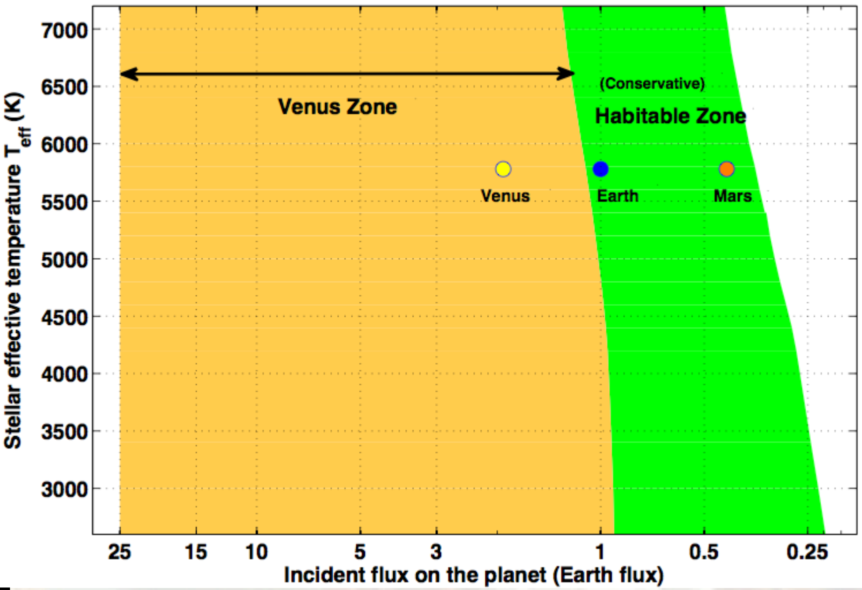
Stephen R. Kane[1], Ravi Kumar Kopparapu[2,3,4,5,6], Shawn D. Domagal-Goldman[7]

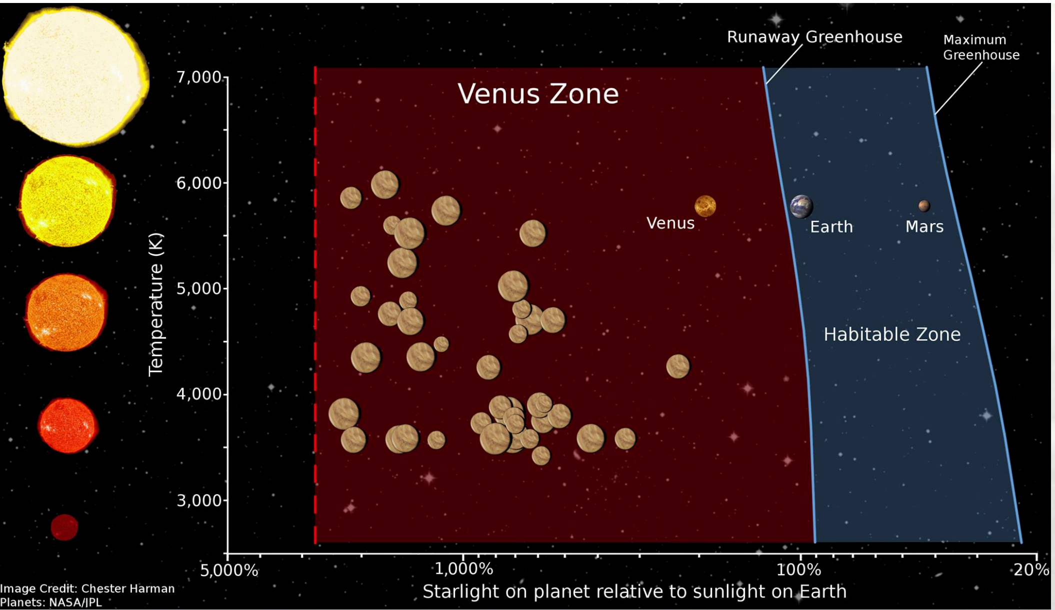
Submitted for publication in the Astrophysical Journal Letters

ABSTRACT

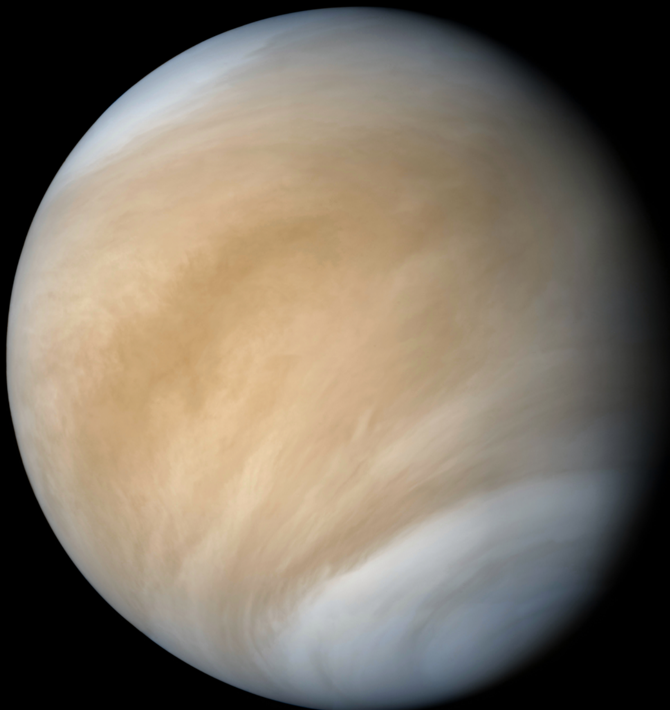
The field of exoplanetary science has seen a dramatic improve
over recent years. Such discoveries have been a key feature of
utilizes the transit method to determine the size of the planet
corresponding interest in the topic of the Habitable Zone (H
analogs. Within the Solar System, there is a clear dichotomy
atmospheric evolution, likely the result of the large difference
the Sun. Since Venus is 95% of the Earth's radius in size, i
these two planets based only on size. In this paper we discuss
atmospheric erosion and runaway greenhouse limits for planets
Zone" (VZ) in which the planet is more likely to be a Venus
We identify 43 potential Venus analogs with an occurrence rat
dwarfs and GK dwarfs respectively.

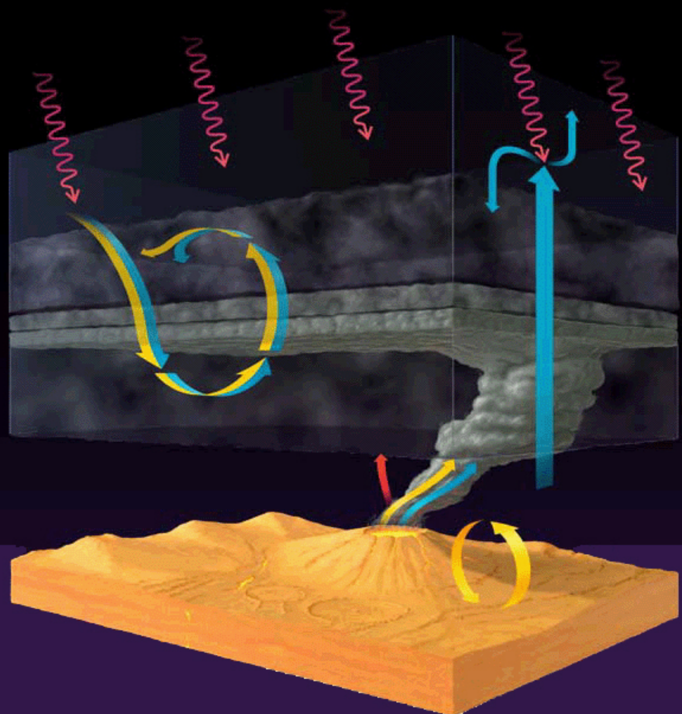
Subject headings: astrobiology – planetary systems – planets a





National Aeronautics and Space Administration



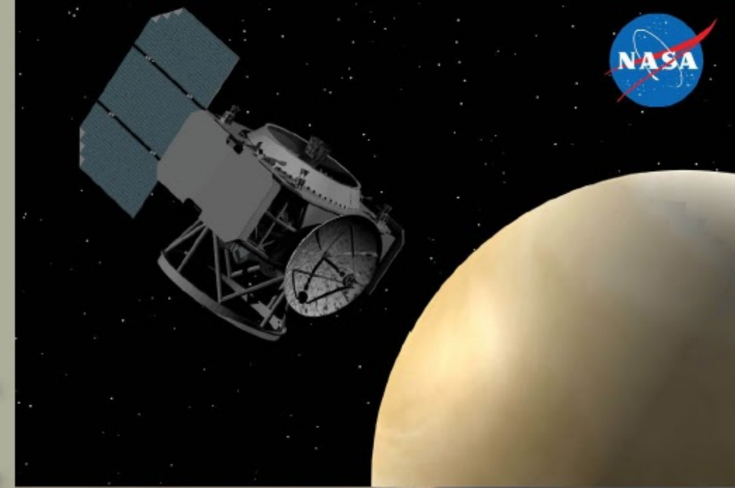


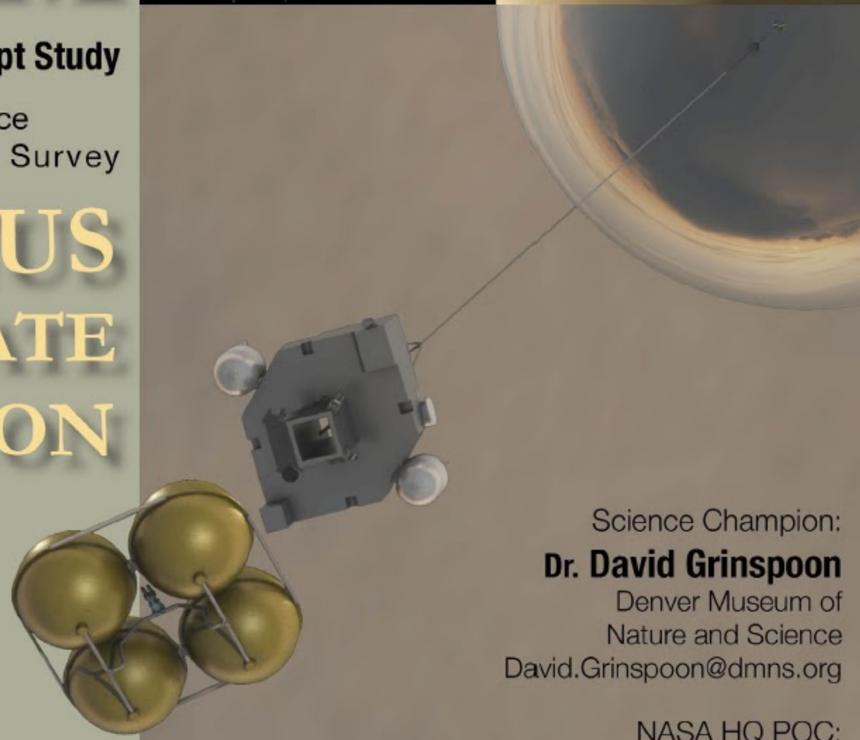
VCM

Mission Concept Study

Planetary Science
Decadal Survey

VENUS CLIMATE MISSION





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