# Ancient Venus climate & observational constraints

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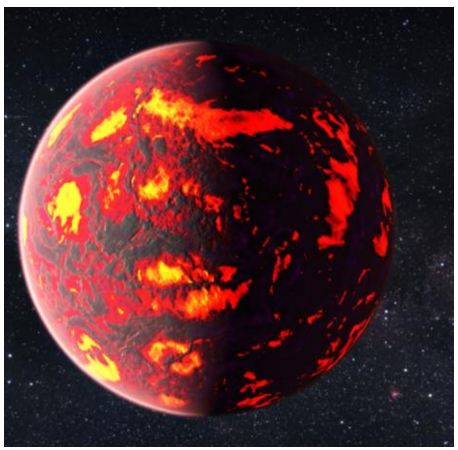
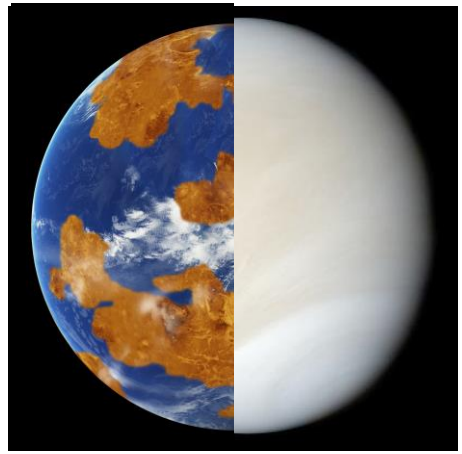
Venera-D 2019 Moscow

# From Magma Ocean to the first stable climate to Today

Earth & Venus



4.5Gya



4 Gya ~1 bar $N_2/CO_2$ **~25 C**

92 bar $CO_2/N_2$ **450 C**

Today 92 bar $CO_2/N_2$

**450 C**

VENUS

3-4 Gya <1 bar $N_2/CO_2/CH_4$

**~15 C**

Today 1 bar $N_2/O_2/CO_2/CH_4$

**~15 C**

EARTH

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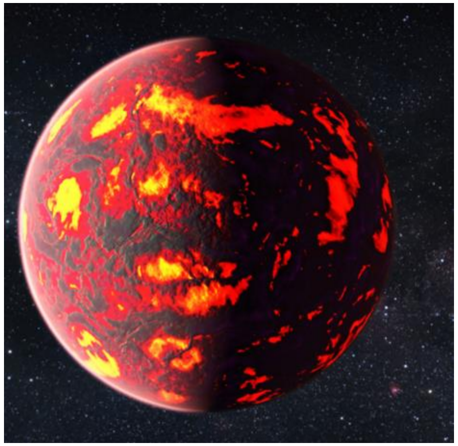
# From Magma Ocean World to the first stable climate?

Earth & Venus



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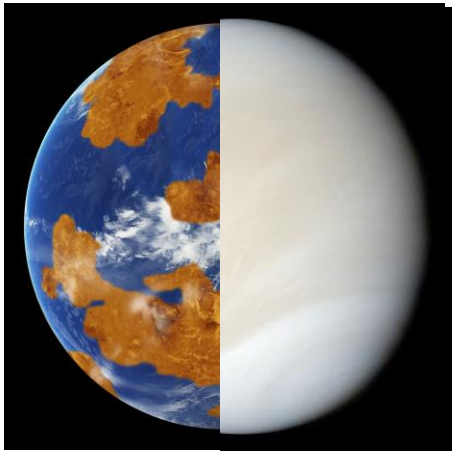


3-4 Gya ???

**Longevity of Magma Ocean crucial**:
1 - 100 Mya
Hamano 2013, Lebrun 2013,
Salvador et al. 2017
Bonati et al. 2019

**Was all water lost < 100Myr?**

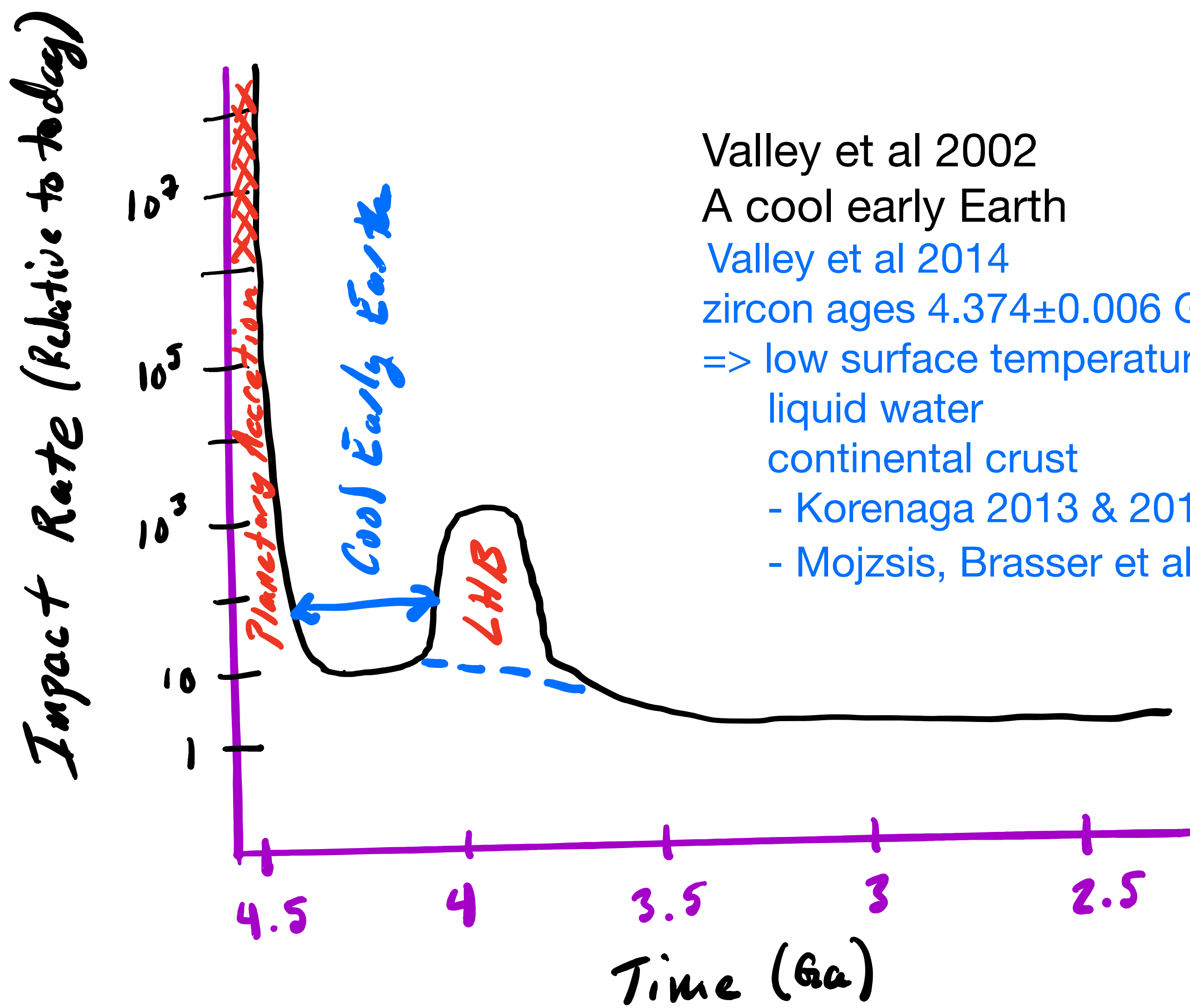
Replenished via Late Veneer?

3-4 Gya ~1 bar ~**15 C**
$N_2/CO_2$ ($CH_4$)

~1My Magma Ocean
Primordial water remains

Late Veneer
contributed 5-30%
R. Greenwood et al. 2018 Sci Adv

# Is a Cool Early Venus Possible?
# Can Comparative Planetology help?

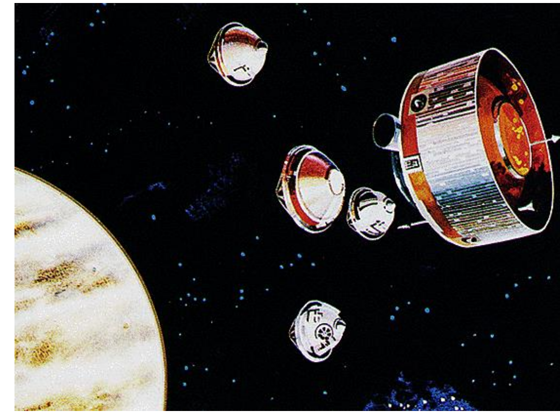



Valley et al 2002
A cool early Earth
Valley et al 2014
zircon ages 4.374±0.006 Ga
=> low surface temperatures
liquid water
continental crust
- Korenaga 2013 & 2018
- Mojzsis, Brasser et al. 2019

Is there evidence for surface liquid water in Venus' history?

If so then **clouds** in concert with **rotation rate** may have played a key role in Venus' climate

# Did Venus have surface liquid water?



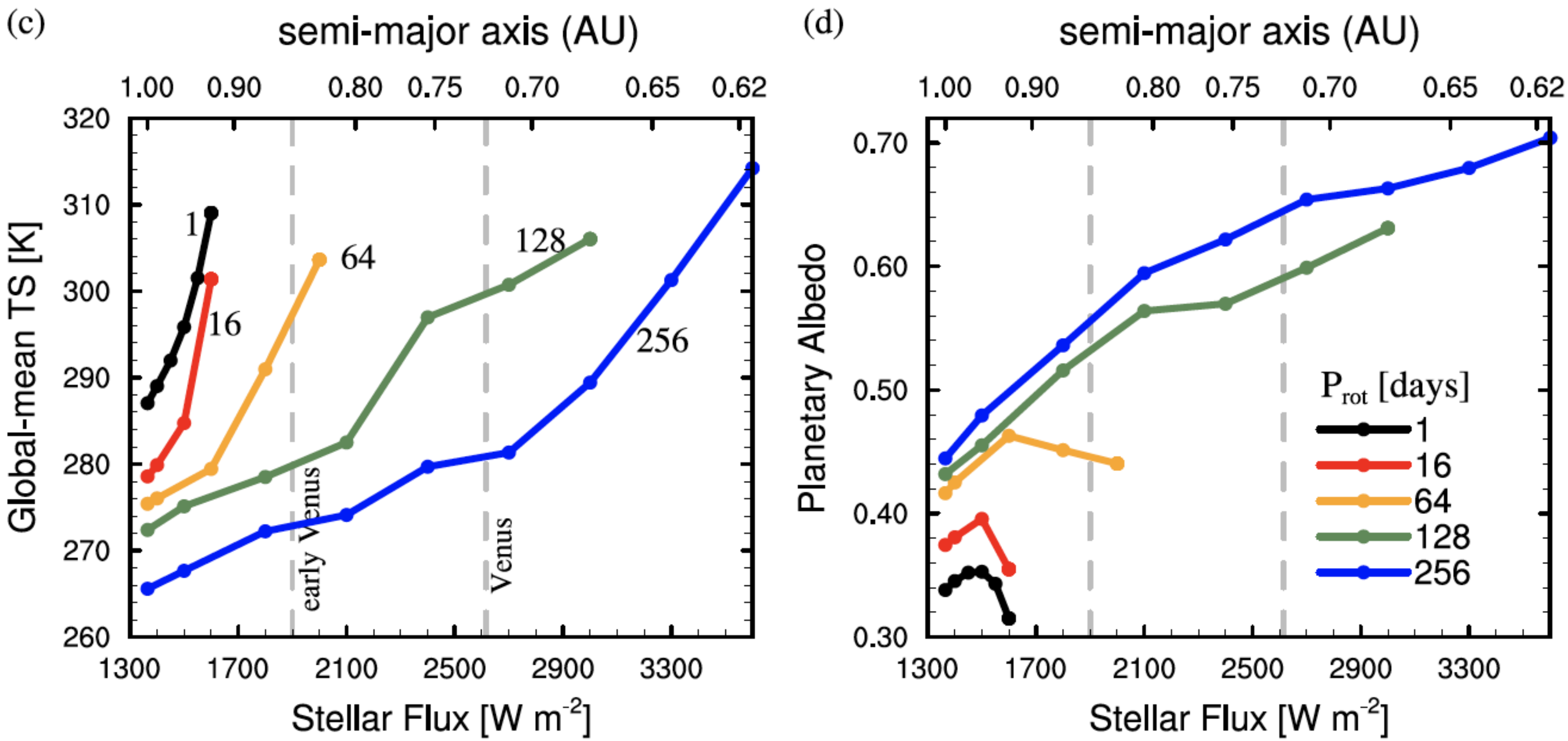
- Primordial $H_2O$ same as Earth?
- High D/H ~150+/-30 x terrestrial --- Pioneer Venus
  - 0.6 – 16% of terrestrial ocean 4-530m (Donahue et al. 1997)
  - **Timescale of $H_2O$ loss unknown**
- Late Veneer
  - Greenwood et al. 2018: Earth received 5-30% of its water in late Veneer -> For Venus a shallow ocean?
- Galileo/NIMS (Hashimoto 2008)
  - highlands mostly composed of felsic rocks -> Granitic?
- Nikolayeva 1990, Shellnut 2019
  - Venera 8 probe encountered a fragment of crust that resembles a terrestrial greenstone belt (modelling dependent!)

*Венера/Venera* 13

# Climatic Importance of Rotation Rate

## Yang et al. 2014 ApJL 787

### Strong Dependence of the inner edge of the habitable zone on planetary rotation rate



# Climatic Importance of Rotation Rate

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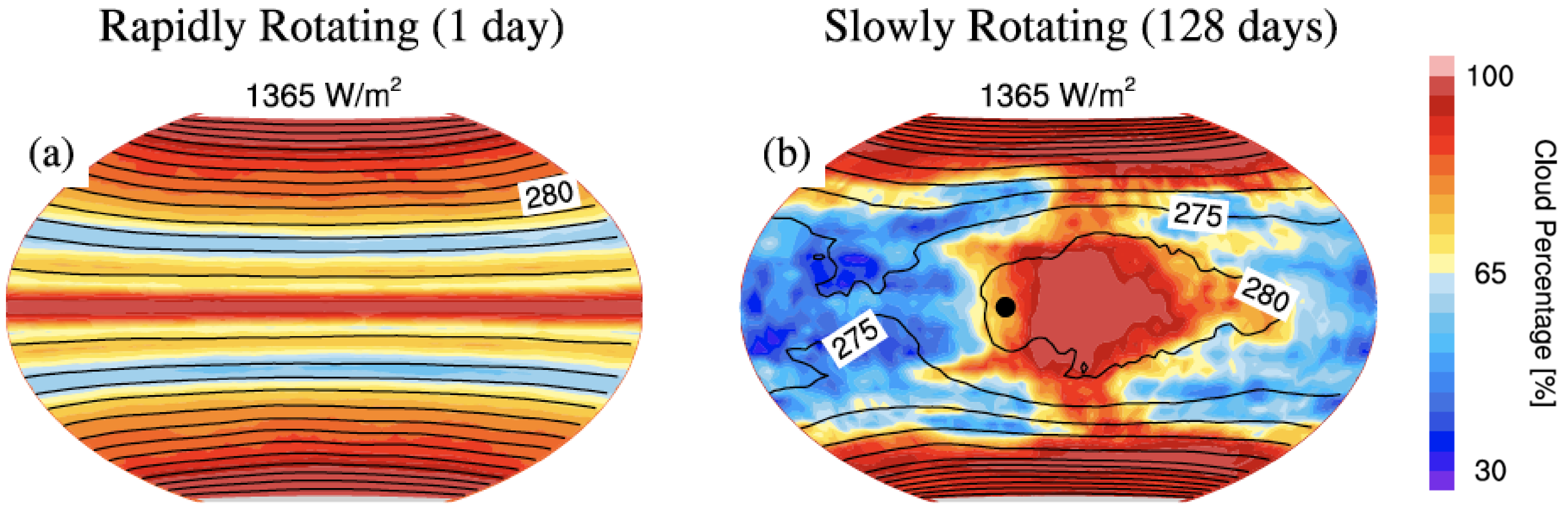


# Venus Rotation & Obliquity

Has it evolved through time?

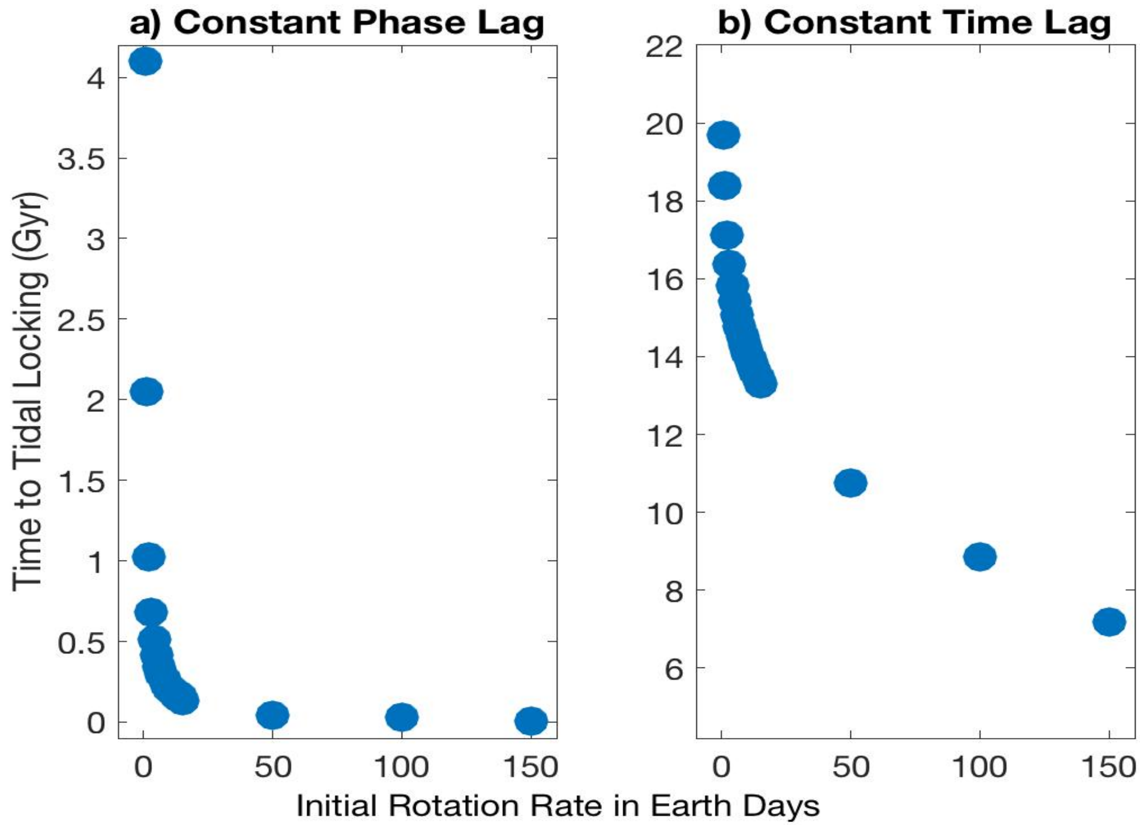
What are prevailing theories today?

# How did Venus end up retrograde?

- Slow retrograde rotation result of a large impactor
  - Alemi & Stevenson 2006
- Core Mantle Friction + Atm Tidal Torque (ATT)
  - Gold & Soter 1969, Goldreich & Peale 1970
  - Dobrovolskis & Ingersoll 1977-1980
  - Laskar & Correia in papers from ~2001
- 1 bar sufficient for ATT (Leconte et al. 2015)
- Solid body tidal dissipation
- Ocean tidal dissipation

# A possible history of Venus' rotation?

Equil Tide Model
Using:
Q=12
$k_2$=0.299




Venus CPL: 3 days -> Synchronous Rotation -> 684Myr (This work)
15 days -> Synchronous Rotation -> 132Myr "
Earth CPL: 3 days -> Synchronous Rotation -> ~4.5Gyr (Barnes 2017)

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Thanks to R. Barnes for eqTide help.

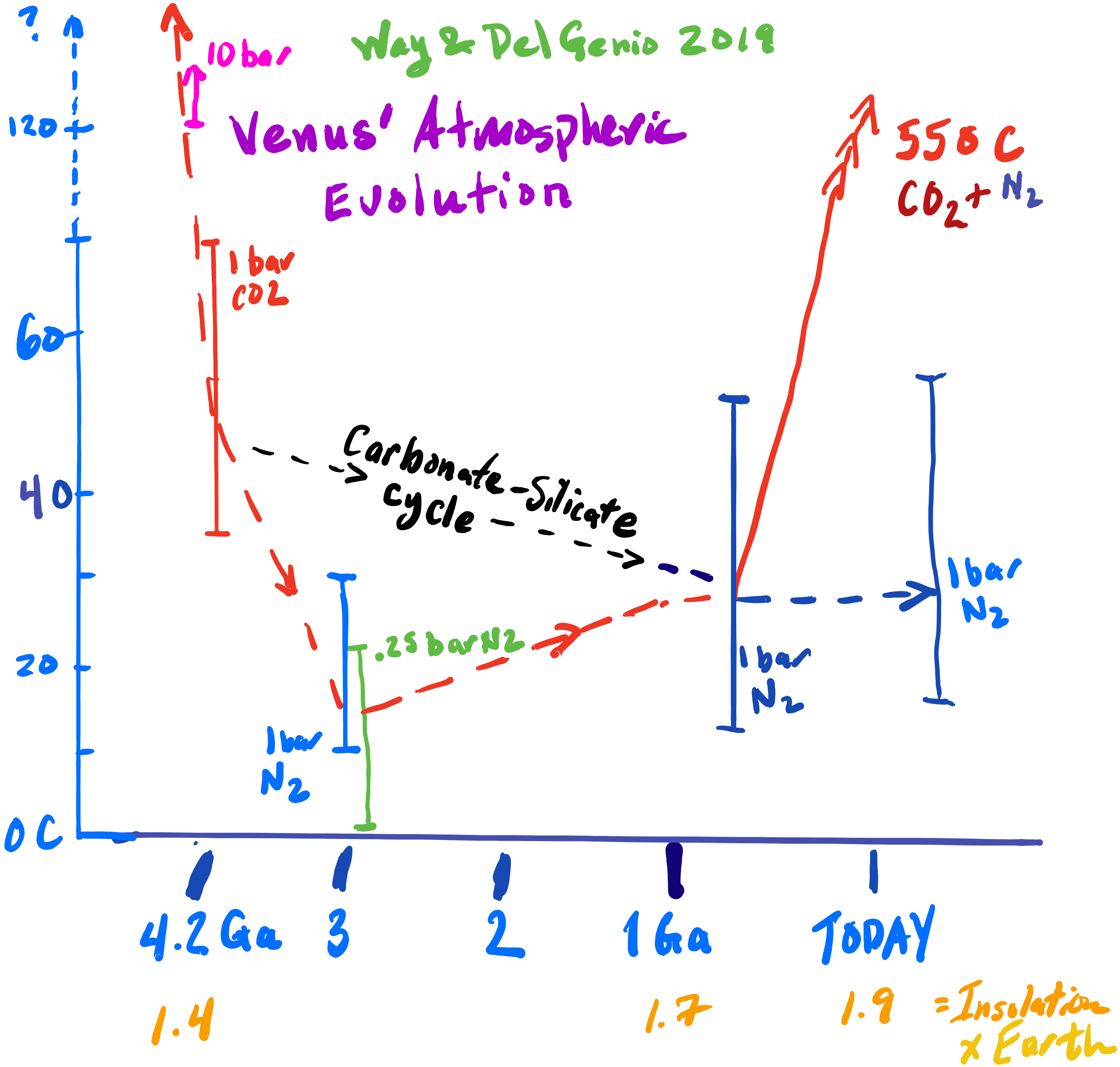
# Consequences of Tidal Dissipation in a Putative Venusian Ocean

(Green, Way & Barnes 2019 Astrophys. J. Lett.)

- Numerical Ocean Tide Model (OTIS)
- Modern Venus topography: 330 & 830m ocean
- Rotational periods –243 to +64 sidereal days
- Tidal dissipation varies 5 orders of magnitude
- **Maximum slow down: 72 days per million years**
- Should not be surprising? (Love 1944, Kozai 1964):
  - Tidal Love Solid Earth < Tidal Love Oceans

# ROCKE-3D (3-D GCM): Venus Ensemble

- **Spin: –243 (sidereal 'Earth days')**
- Atmospheres:
  - 4.2Ga (S0X=1.4) : $CO_2$ (100%) 1 bar & 10 bar
  - 2.9Ga (S0X=1.47): $N_2/CO_2/CH_4$ (Modern Earth)
  - 0.7Ga (S0X=1.7) : $N_2/CO_2/CH_4$ (Modern Earth)
  - Today (S0X=1.9) : $N_2/CO_2/CH_4$ (Modern Earth)
- Topography/Ocean
  1. Abe Type Dune world (20cm in soil only) <limited $H_2O$>
  2. 10m water equivalent in lakes
  3. 310m deep ocean
  4. Modern Earth Topography with 310m bathtub ocean
  5. Aquaplanet: 158m deep ocean

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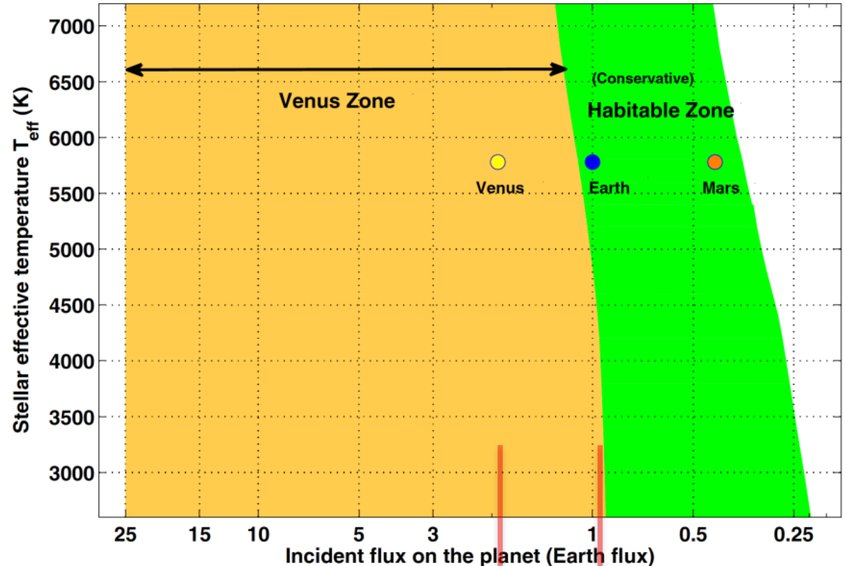
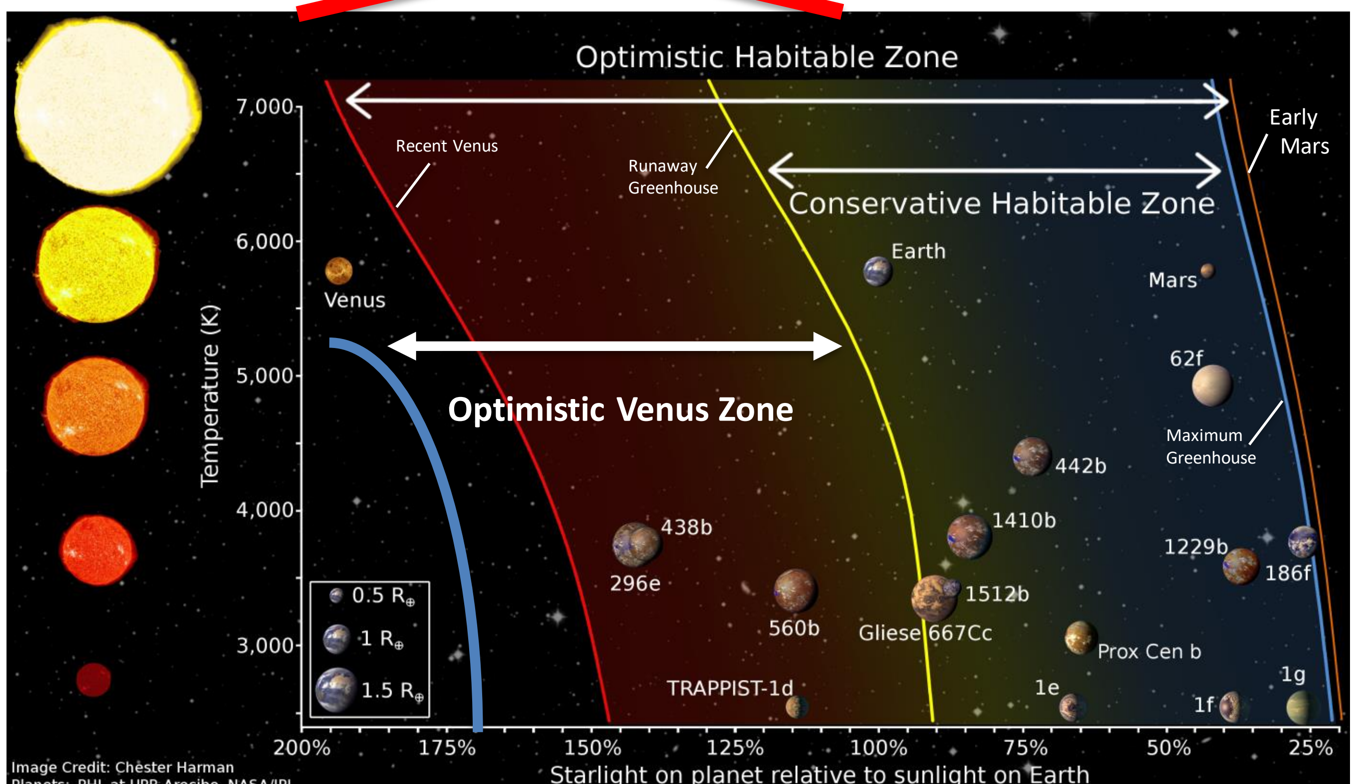
## The Venus Zone (VZ) (Kane et al. 2014)




## The Optimistic Venus Zone (OVZ)

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# Observables: In situ He/Ne/Ar/Kr/Xe:

- Radiogenic noble-gas isotopes reflect processes that occurred over one or two half-lives of the parent species, and therefore a suite of isotopes sensitive to different timescales can be used to probe the evolution of planetary atmospheres. (Kevin Baines et al. 2013 CCTP2 Book)
- IF one can model the escape processes correctly!
  - E.g. 1: difficult for Helium
  - E.g. 2: Xenon ionizes more easily than Hydrogen and hence it can be dragged away by the escaping wind.

# Water

- Pioneer Venus: D/H = 150 +/- 30
- Venus Express: D/H = 240 +/- 25
- D/H varies with altitude (*Federova et al.* 2008)
- High D/H may only reflect last 0.5Gyr (Grinspoon 1993)
- *Baines 2013: in situ* isotopic ratios of 15N/14N & HDO/H2O to 5% (latter over range of altitudes to assess photochemical & escape fractionation effects) would provide insights into understanding
  - present & past escape rates
  - the nature of Venus' likely water-rich ancient climate
  - the role of comets in supplying volatiles to the inner planets.
- 129Xe would indicate whether Venus lost much of its original atmosphere during its first ~100Myr

Baines et al. 2013

TABLE 1. Atmospheric compositions of the terrestrial pla

| Constituent | Primary Diagnostics | Venus |
|---|---|---|
| *Noble-Gas Abundance (VMR)* | | |
| $^{132}Xe$ | Planetary origin: Atmospheric blow-offs Cometary/planetesimal impacts | Not measured; expected: ~1.9 × $10^{-9}$[a,b] |
| $^{84}Kr$ | Planetary origin: Role of cold comets | (7.0 ± 3.5) × $10^{-7}$ (Venera)[d] or (5.0 ± 2.5) × $10^{-8}$ (PV)[d] |
| $^{36+38}Ar$ | Planetary origin: Roles of comets and planetesimals | ~(7.5 ± 3.5 ) × $10^{-5}$[f] |
| $^{40}Ar$ | Evolution: Interior outgassing | (7 ± 2.5) × $10^{-5}$[d] |
| $^{20}Ne$ | Planetary origin: Common origin of Venus, Earth, Mars? | (7 ± 3) × $10^{-6}$[d] |
| $^{4}He$ | Evolution: Interior outgassing | [1.2 (+2.4,−0.8)] × $10^{-5}$[d] |
| *Noble-Gas Isotopic Ratio* | | |
| $^{129}Xe/^{132}Xe$ | Early evolution: Large atmospheric blow-off | Not measured; expected: ~3 |
| $^{136}Xe/^{132}Xe$ | Origin/evolution: U–Xe hypothesis | Not measured; expected: ~1 |
| $^{40}Ar/^{36}Ar$ | Early history: Interior outgassing | 1.03 ± 0.04[l] or 1.19 ± 0.07[m] |
| $^{36}Ar/^{38}Ar$ | Late formation: Large impact | 5.6 ± 0.6[l] or 5.08 ± 0.05[n] |
| $^{21}Ne/^{22}Ne$ | Origins: Common planet origin hypothesis | Not measured; expected: <0.067 |
| $^{20}Ne/^{22}Ne$ | Early evolution: Hydrodynamic escape | 11.8 ± 0.7[a] |
| $^{3}He/^{4}He$ | Early evolution: Impact of solar wind | Not measured; expected: <3 × $10^{-4}$[d] |

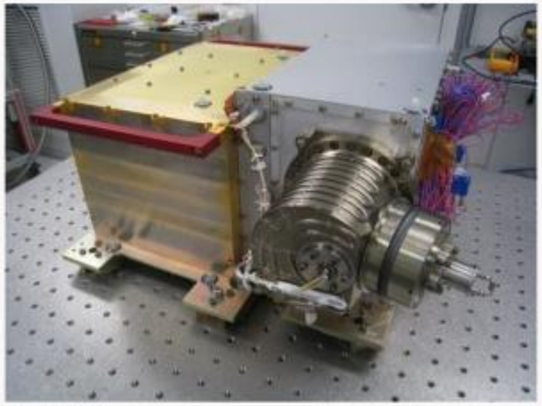
Baines et al. 2013

| | | |
|---|---|---|
| *Light-Element Isotopic Ratio* | | |
| D/H | Evolution: Loss of H/water | 0.016 ± 0.002[p]<br>0.064–0.08 above 70 km alt.[q] |
| $^{14}N/^{15}N$ | Evolution: Atmospheric loss since planetary formation | 273 (+70,–46)[r] |
| $^{16}O/^{17}O$ | Origin: Common kinship of terrestrial planets | Not measured |
| $^{16}O/^{18}O$ | Origin: Common kinship of terrestrial planets | 500 ± 25[l] |
| $^{33}S/^{32}S$ | Past/current volcanic activity, magmatic composition | Not measured; expected: ~$8 \times 10^{-3}$ |
| $^{34}S/^{32}S$ | Past/current volcanic activity, magmatic composition | Not measured; expected: ~0.04 |
| $^{12}C/^{13}C$ | Biological marker | 88 (+2,–1)[n] |
| $CO_2$ | Dominant original atmospheric constituent | 0.965 ± 0.08[d] |
| $N_2$ | Second most prevalent original atmospheric constituent | 0.035 ± 0.08[d] |
| $O_2$ | Disequilibrium species; indicator of biology | $<1 \times 10^{-6}$ @60 km alt.<br>$4 \times 10^{-5}$ @50 km<br>$1.6 \times 10^{-5}$ near surface[d,s] |
| *Bulk Abundances (VMR)* | | |
| CO | Venus: Hot thermochemistry<br>Tracer of meridional circulation | $2.5 \times 10^{-5}$ @35 km alt.<br>$(3–20) \times 10^{-5}$ @60–150 km alt.[d,s] |
| $H_2O$ | Geologic styles; Earth, Venus: Condensable<br>Earth: Weather cycle | $(4.4 \pm 0.9) \times 10^{-5}$ @0–40 km<br>$2 \times 10^{-4}$ @50 km<br>$1 \times 10^{-6}$ @60 km[d,s] |
| $H_2$ | Photochemistry | $(2.5 \pm 1.0) \times 10^{-6}$ at 50–60 km[s] |
| $H_2O_2$ | Photochemistry | None detected |
| $O_3$ | Photochemistry | None detected |
| $CH_4$ | Disequilibrium species; biological marker | None detected |

# Crucial for understanding Venus!

## Neutral Gas and Ion Mass Spectrometer (NGIMS)

The Neutral Gas and Ion Mass Spectrometer (NGIMS) measures the composition and isotopes of thermal neutrals and ions.



The NGIMS instrument measures the composition and isotopes of thermal neutrals and ions in the Martian atmosphere. (Courtesy NASA/GSFC)

**Goals:**

- Determine structure and variation of neutral atmosphere and ionosphere with altitude over the globe from the homopause to above the exobase where the neutral gas can escape
- Provide a basis for the study of thermospheric energetics, transport, circulation and formation of the ionosphere
- Reveal the effects of lower atmospheric effects on the composition of the upper atmosphere and escape

**Observations:**

- Basic structure of the upper atmosphere (major species He, N, O, CO, $N_2$, NO, $O_2$, Ar, and $CO_2$) and ionosphere from the homopause to above the exobase
- Stable isotope ratios, and variations

**Technical details and heritage:**

- Quadrupole Mass Spectrometer with open and closed sources
  - Open source: neutrals and ions
  - Closed source: non-reactive neutrals
- Mass Range: 2 - 150 Da
- Mass Resolution: 1 Da
- Modes: scan entire spectra or adapt to fixed masses
- Sensitivity: $10^{-2}$ (counts/s)/(particles/cm$^{-3}$)
- Heritage from Galileo GPMS, Pioneer Venus ONMS, CASSINI INMS, Contour NGIMS

The MAVEN NGIMS instrument undergoes final preparations for integration onto the spacecraft at Lockheed Martin. (Courtesy NASA/GSFC)

**Instrument publications:** (sorted by most recent at top)

- Thermal Structure of the Martian Upper Atmosphere from MAVEN NGIMS
  (*Journal of Geophysical Research—Planets* article—published online September 2018)—Download PDF (4 MB)

# Conclusions

- Our picture of Venus' evolution requires: **surface liquid water** & **a slowly rotating Venus**
- **If** "A Cool Early Venus" had surface liquid water 4.2Ga then **solar luminosity is NOT the defining factor in its climate evolution**
- Need Venus **in-situ** observations to confirm its geologic & volatile history (HDO/$H_2O$/He/Ne/Ar/Kr/Xe)
- Will Venus' history constrain possible exoplanetary climates?
  - Depends if we go back to the surface of Venus or not.