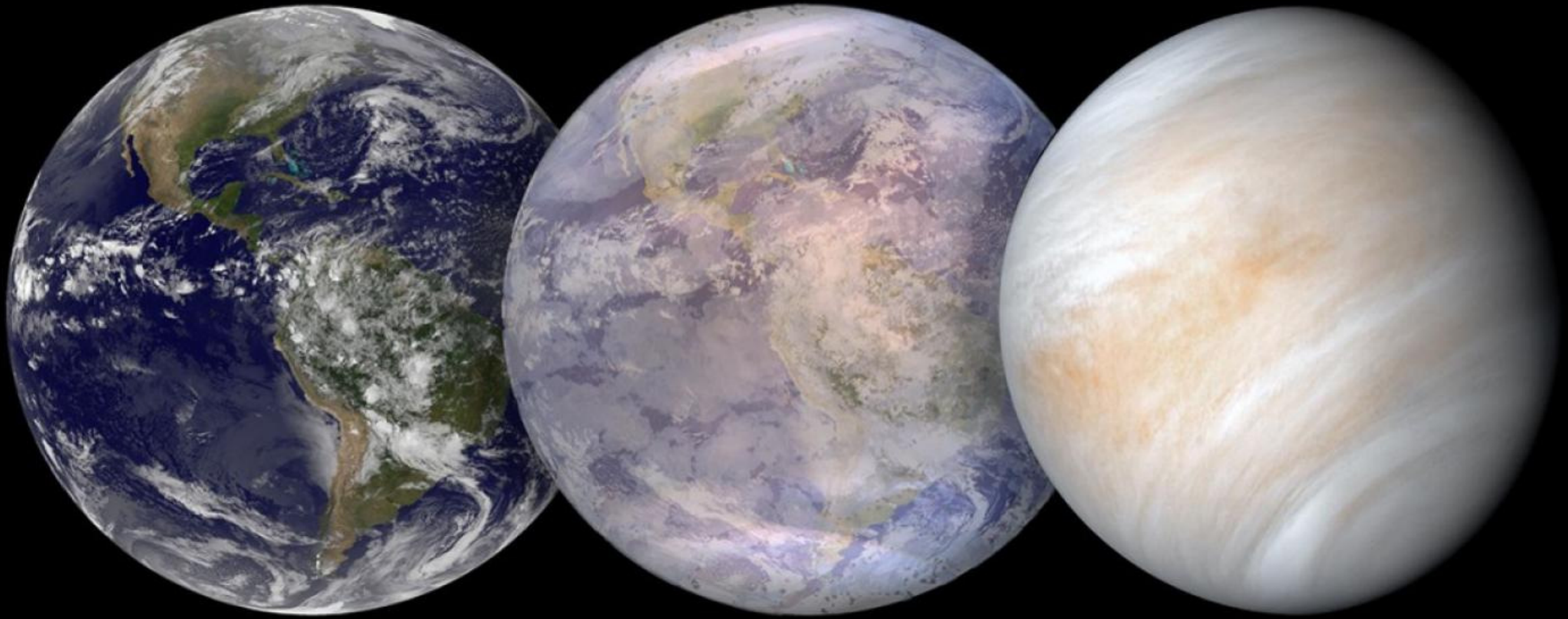
# Planetary Habitability

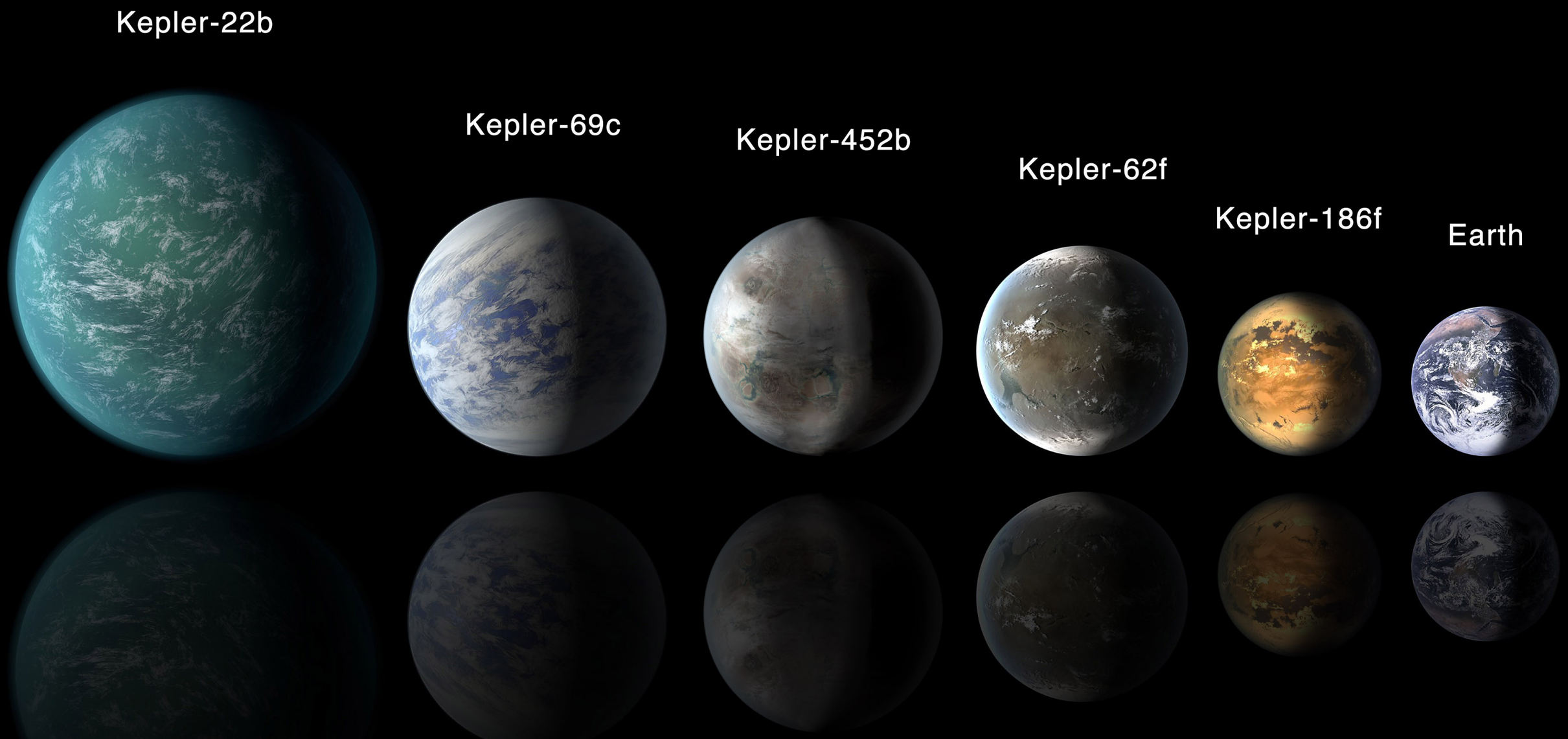


Stephen Kane

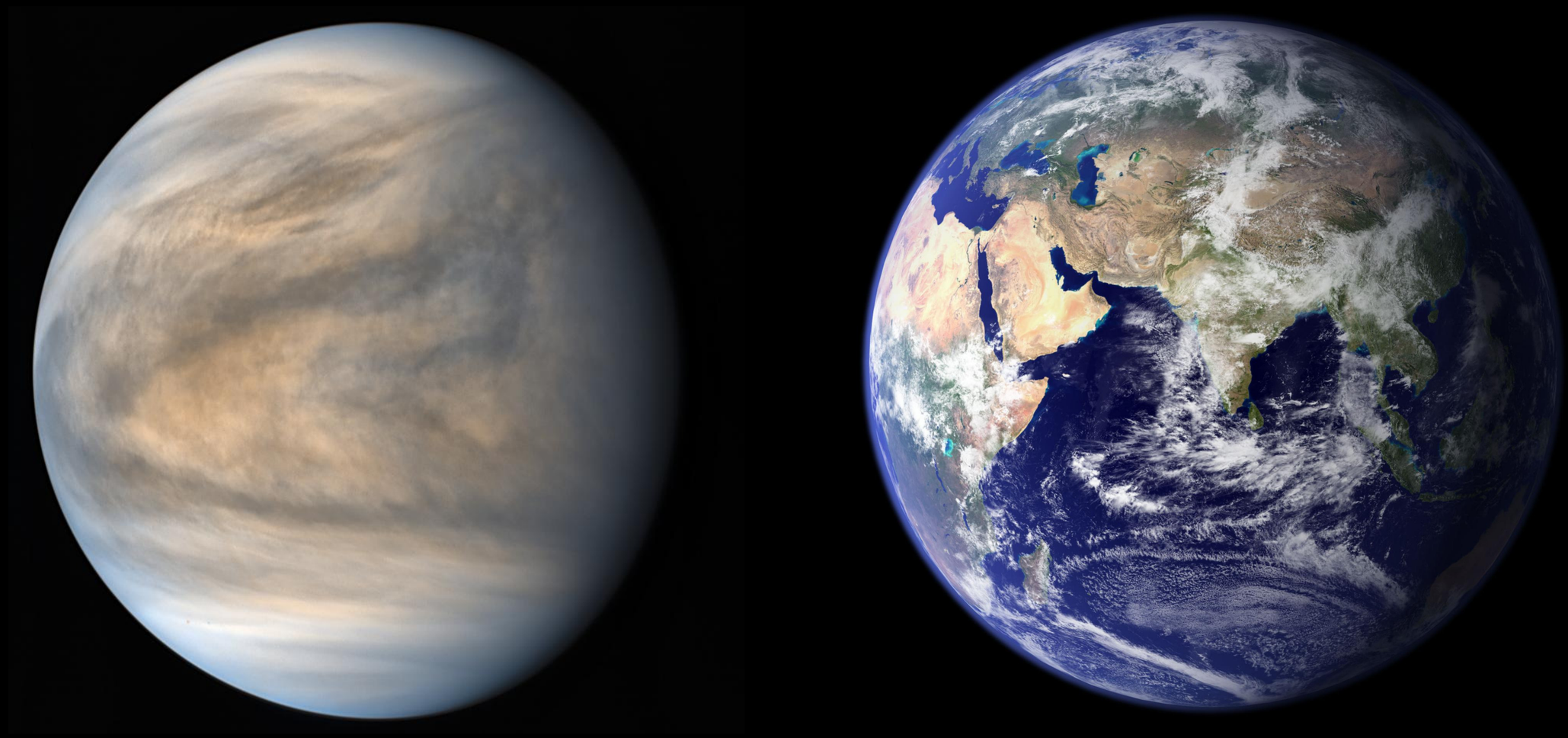
UNIVERSITY OF CALIFORNIA
UC RIVERSIDE

# Planetary Habitability

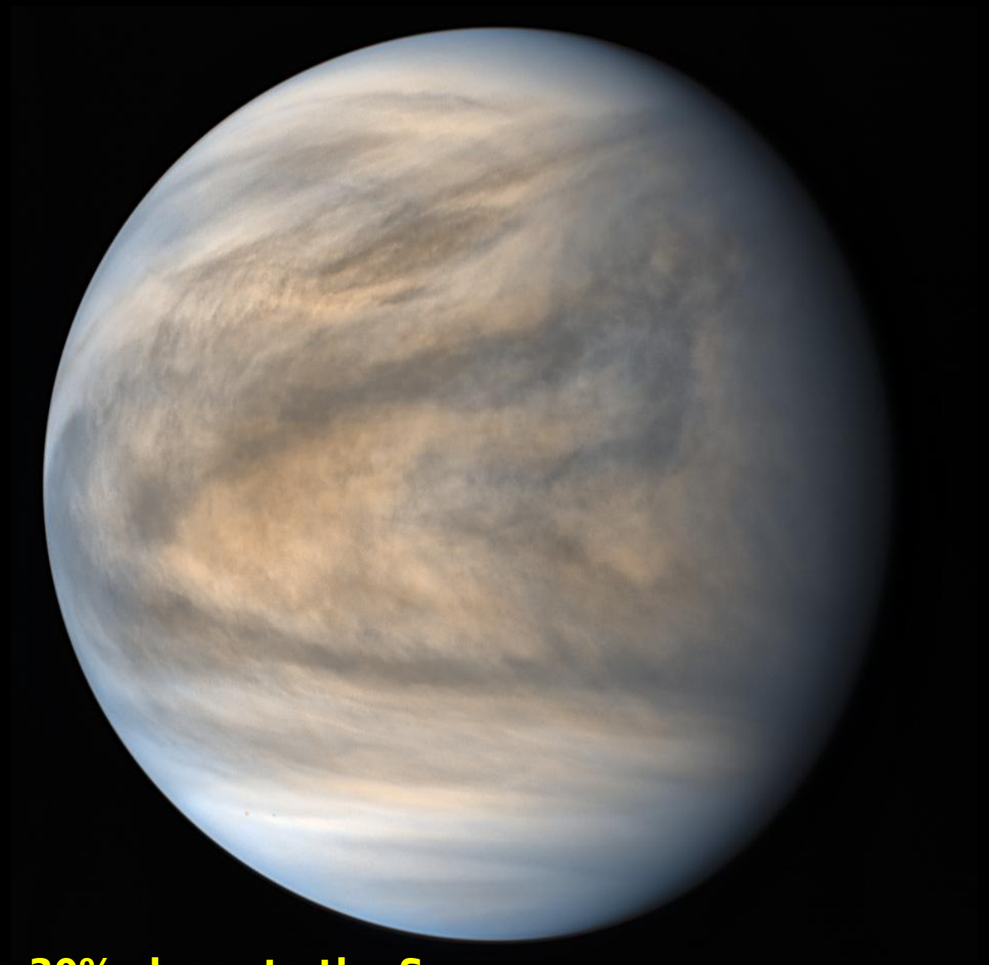
- Lecture 1: The Fundamentals of Planetary Habitability
- Lecture 2: Habitability Lessons Learned from our Sister Planet
- Lecture 3: Stars and the Planetary Energy Balance
- Lecture 4: The Habitable Zone and Orbital Dynamics




**The occurrence rate of planets increases to smaller sizes.**

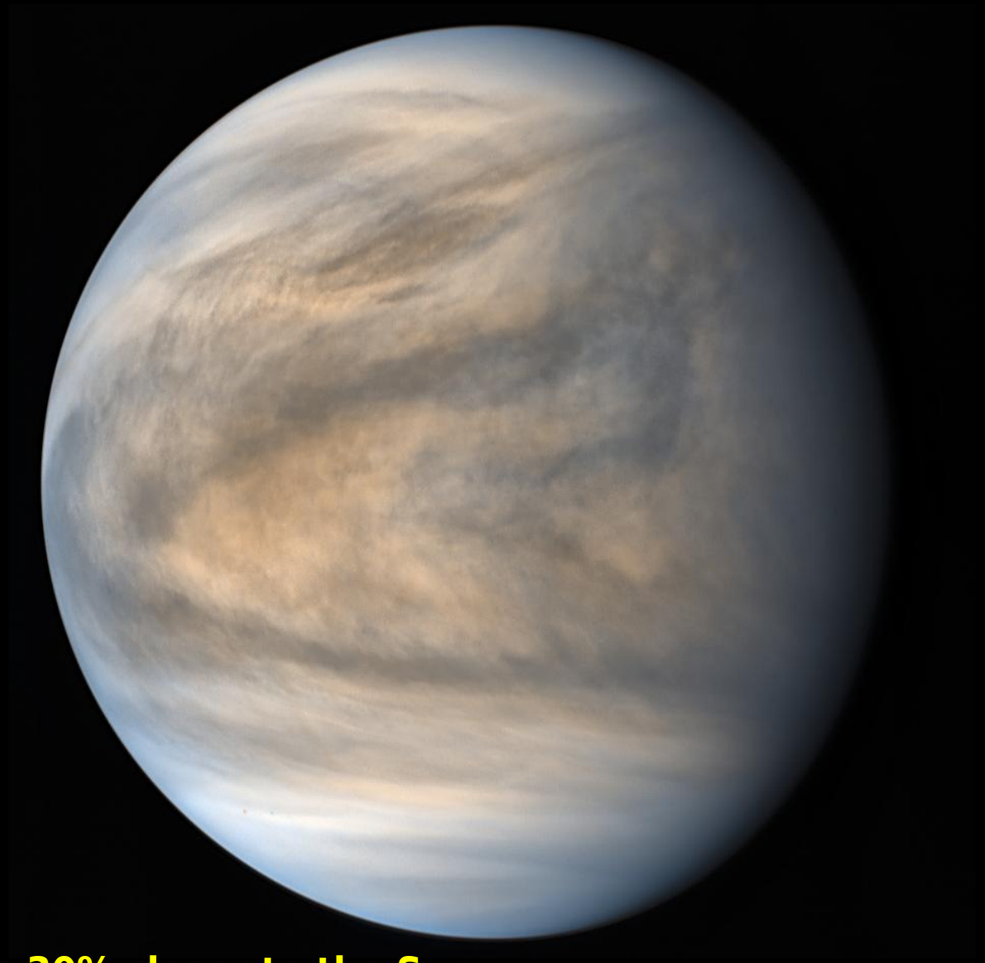


# Venus & Earth: Evolutionary Factors



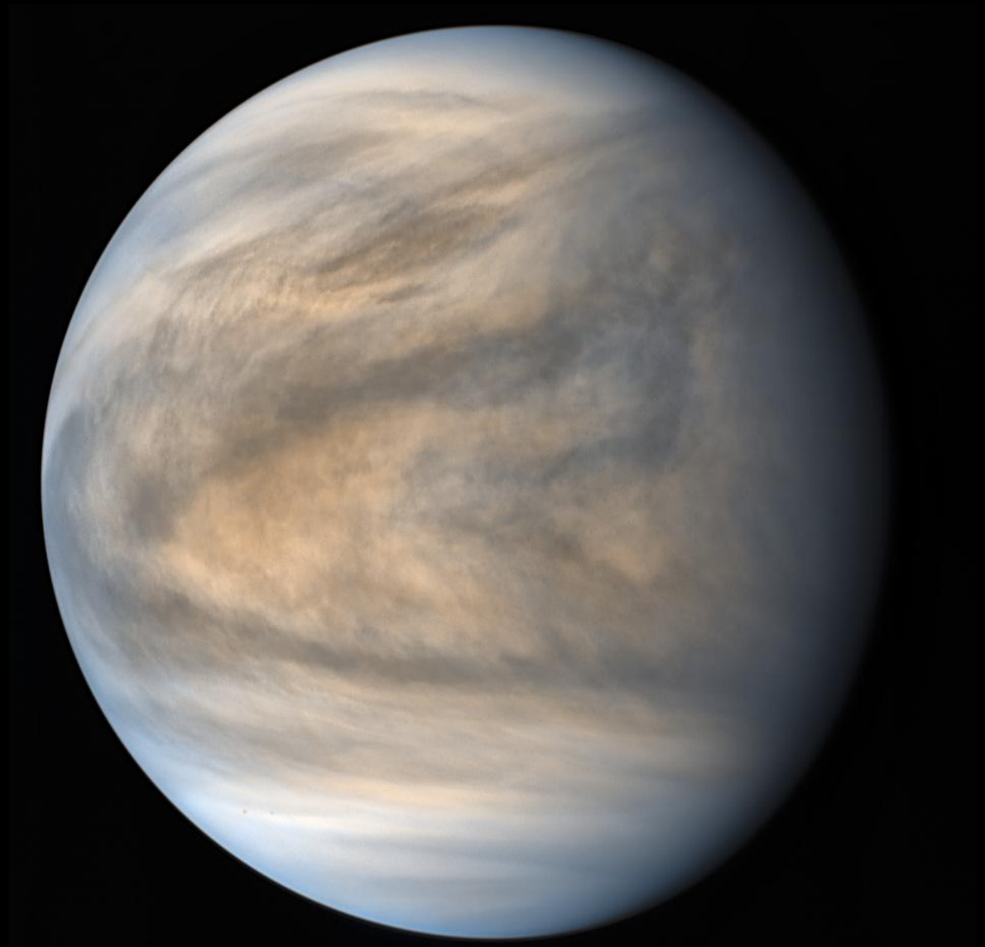
- 30% closer to the Sun.
- Receives twice the amount of solar energy.

# Venus & Earth: Evolutionary Factors



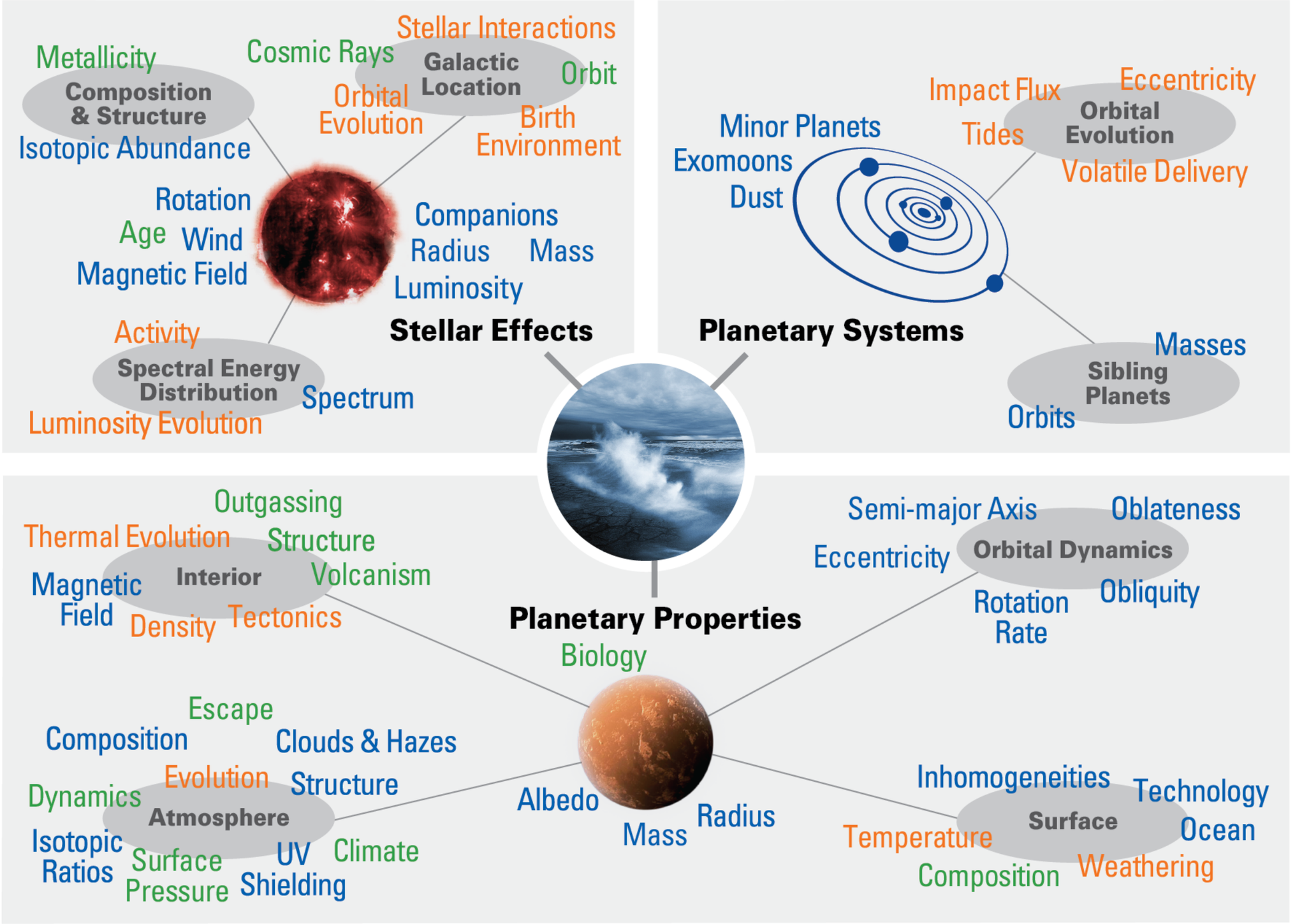
- **30% closer to the Sun.**
- **Receives twice the amount of solar energy.**
- **Rotates very slowly backwards.**
- **Almost vertical rotational axis.**
- **Little to no surface subduction.**
- **Negligible magnetic field.**
- **No substantial moon.**

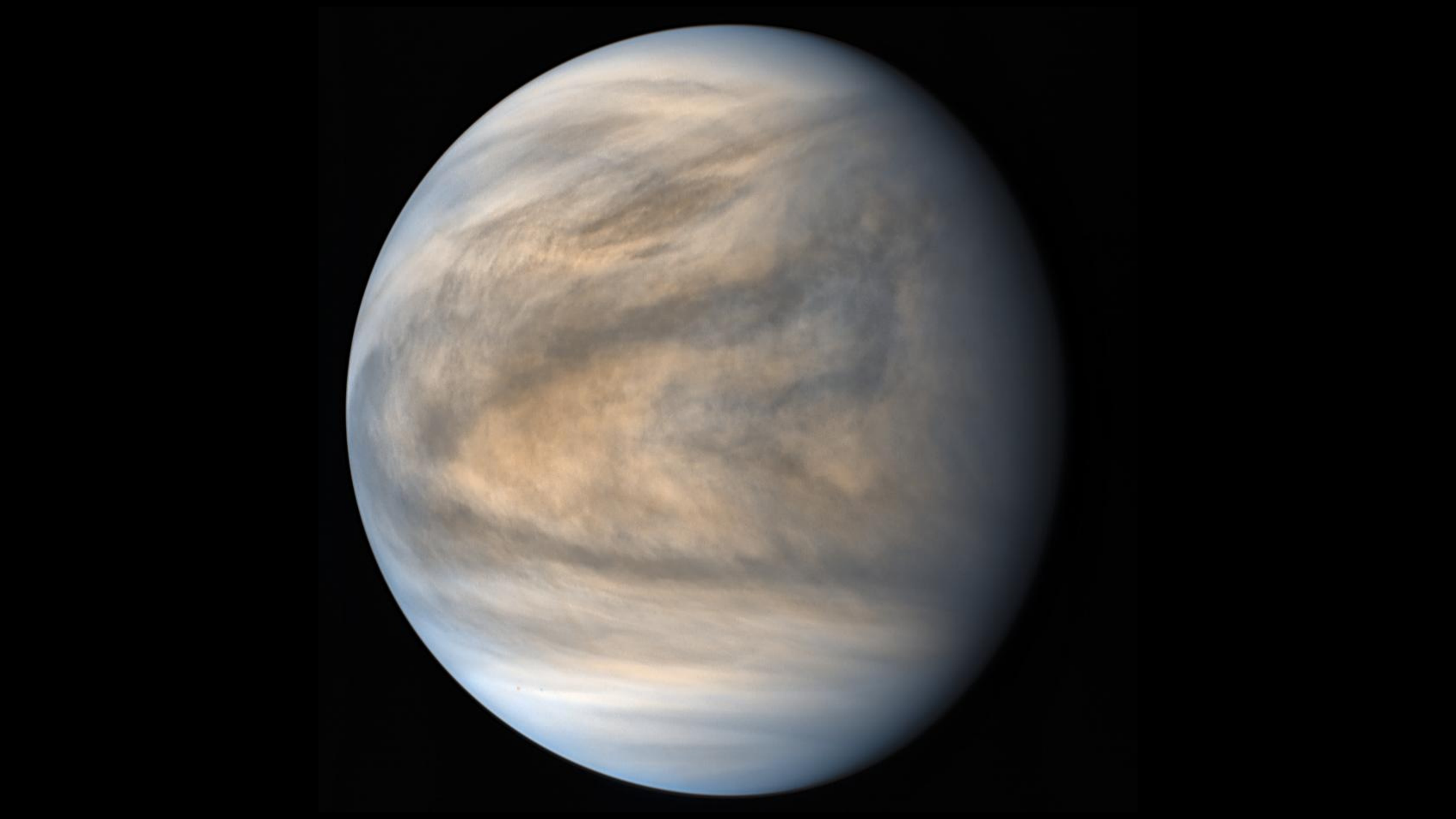
# Venus & Earth: Evolutionary Factors

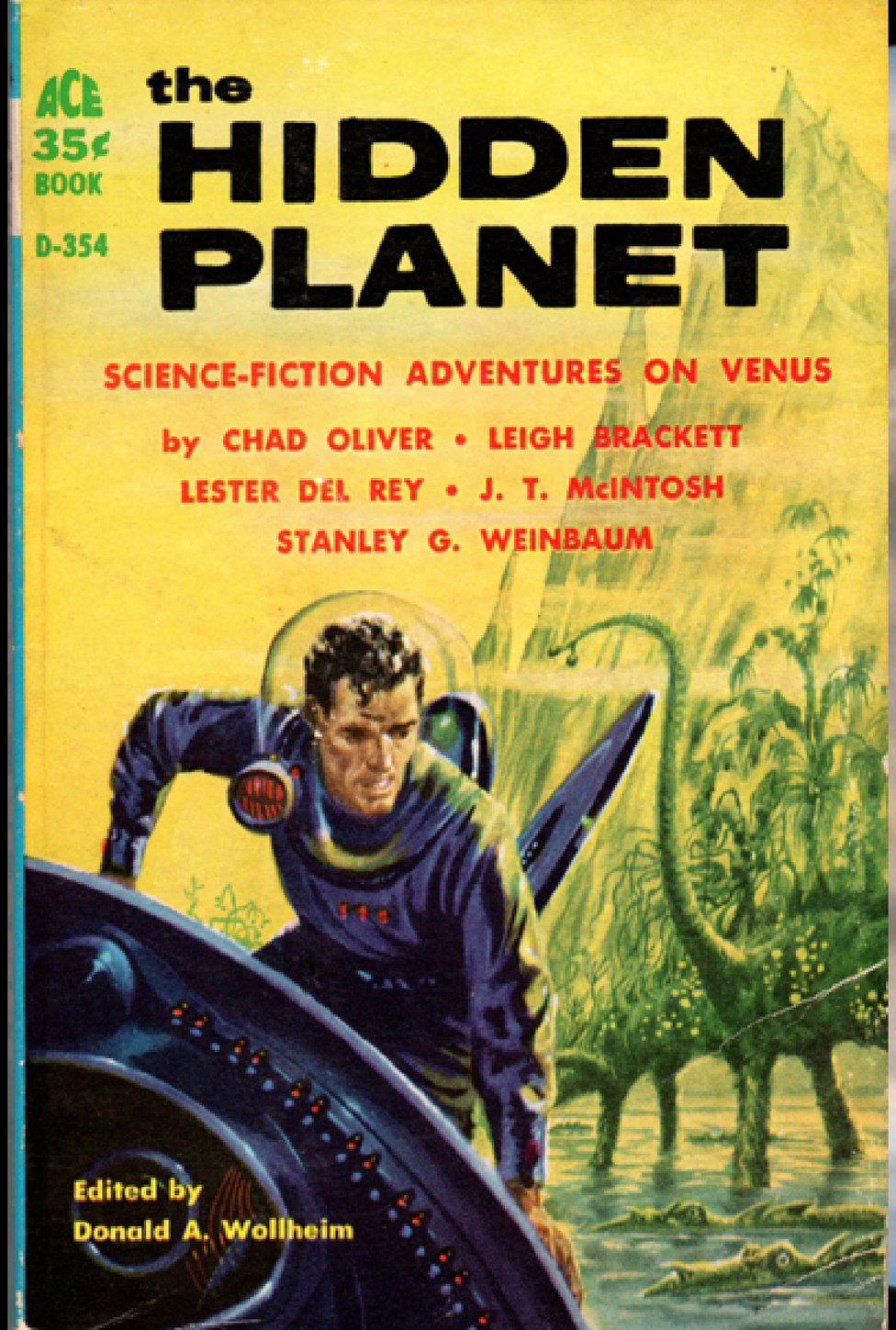


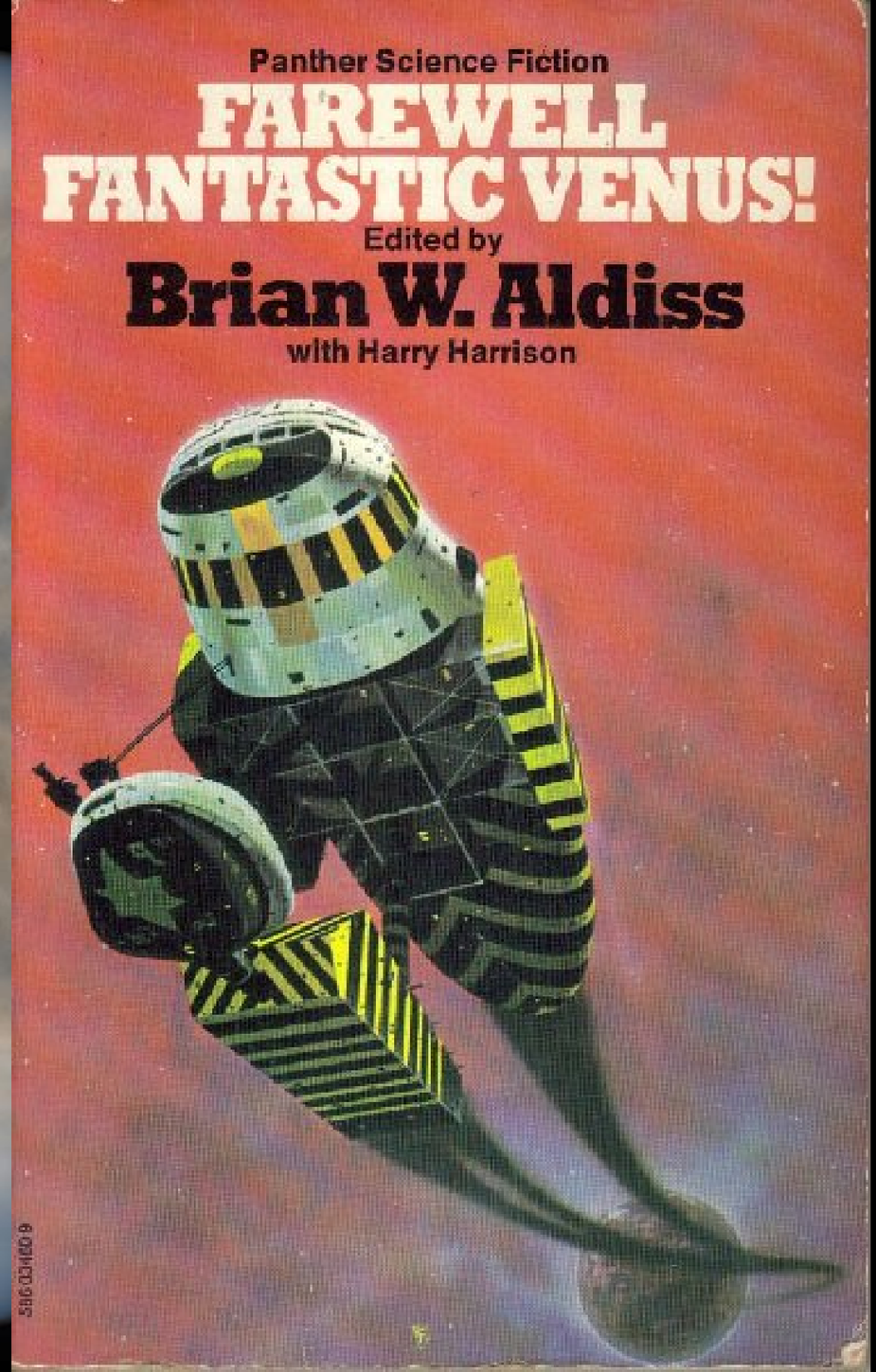
- 30% closer to the Sun.
- Receives twice the amount of solar energy.
- Rotates very slowly backwards.
- Almost vertical rotational axis.
- Little to no surface subduction.
- Negligible magnetic field.
- No substantial moon.

**What is the relative weighting of evolutionary factors?**


Stellar Interactions
Metallicity
Cosmic Rays
Galactic Location
Orbit
Composition & Structure
Orbital Evolution
Birth Environment
Isotopic Abundance
Rotation
Companions
Age
Wind
Radius
Mass
Magnetic Field
Luminosity
Activity
Spectral Energy Distribution
Spectrum
Luminosity Evolution
Stellar Effects
Impact Flux
Eccentricity
Minor Planets
Tides
Orbital Evolution
Exomoons
Volatile Delivery
Dust
Planetary Systems
Masses
Sibling Planets
Orbits
Outgassing
Thermal Evolution
Structure
Interior
Volcanism
Magnetic Field
Density
Tectonics
Semi-major Axis
Oblateness
Eccentricity
Orbital Dynamics
Obliquity
Rotation Rate
Planetary Properties
Biology
Escape
Composition
Clouds & Hazes
Evolution
Structure
Dynamics
Atmosphere
Albedo
Radius
Mass
Isotopic Ratios
Surface Pressure
UV Shielding
Climate
Inhomogeneities
Technology
Surface
Temperature
Ocean
Composition
Weathering




ACE
35¢
BOOK
D-354
the
HIDDEN
PLANET
SCIENCE-FICTION ADVENTURES ON VENUS
by CHAD OLIVER • LEIGH BRACKETT
LESTER DEL REY • J. T. McINTOSH
STANLEY G. WEINBAUM
Edited by
Donald A. Wollheim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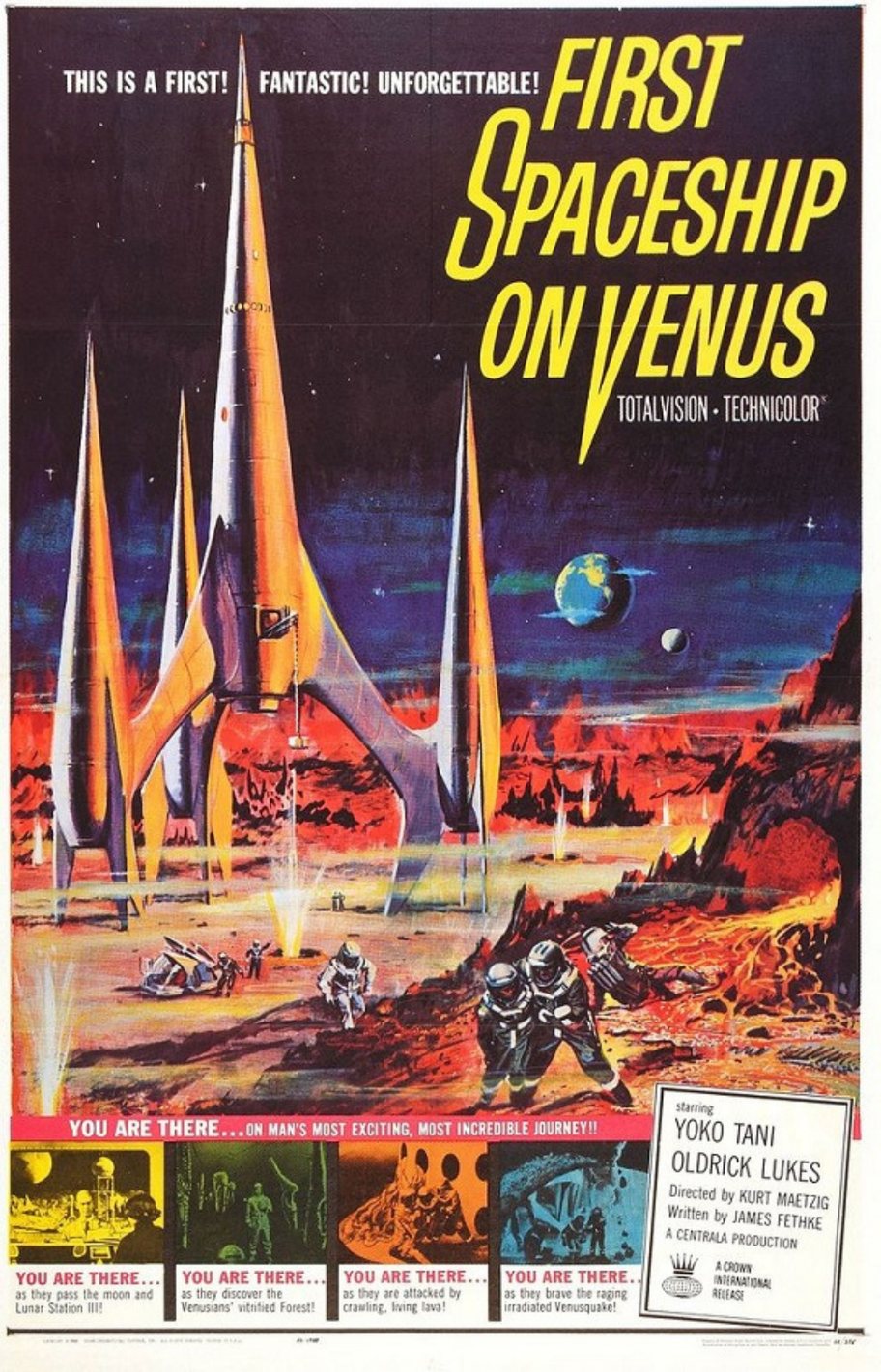
FAREWELL
FANTASTIC VENUS!
Edited by
Brian W. Aldiss
with Harry Harrison


THE THREE STOOGES
HAVE ROCKET, WILL TRAVEL
THEIR FIRST FULL LENGTH FEATURE MOTION PICTURE!
with JEROME COWAN · ANNA-LISA · BOB COLBERT · Written by RAPHAEL HAYES · Produced by HARRY ROMM · Directed by DAVID LOWELL RICH
A COLUMBIA PICTURE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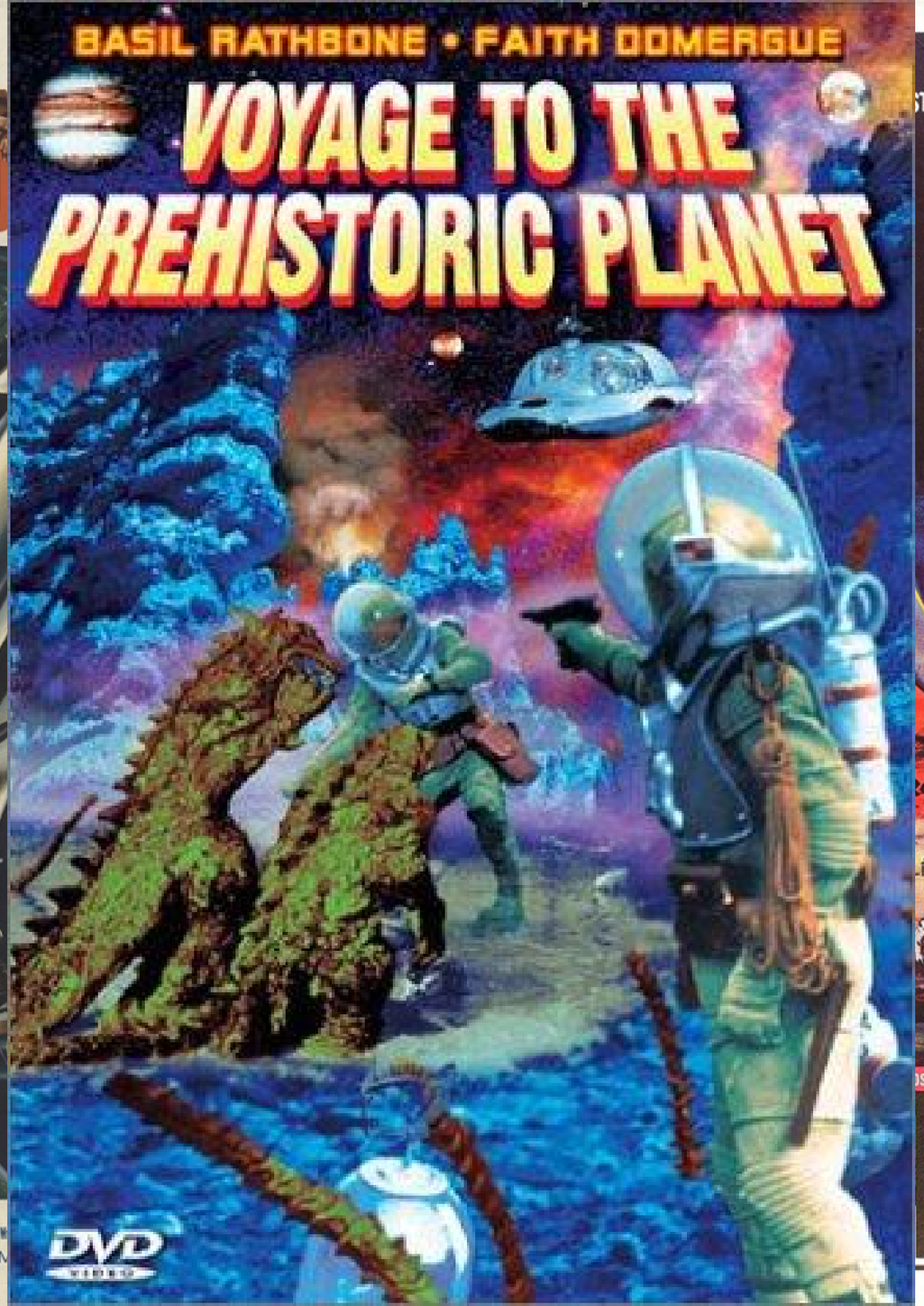
YOU ARE THERE... as they discover the Venusians' vitrified Forest!
YOU ARE THERE... as they are attacked by crawling, living lava!
YOU ARE THERE... as they brave the raging irradiated Venusquake!
starring YOKO TANI OLDRICK LUKES
Directed by KURT MAETZIG
Written by JAMES FETHKE
A CENTRALA PRODUCTION
A CROWN INTERNATIONAL RELEASE


THE
THREE STOO
with
JEROME COWAN · ANNA-LISA · BOB COLBERT ·
A COLU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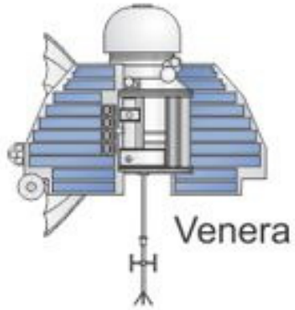
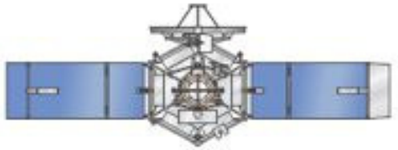
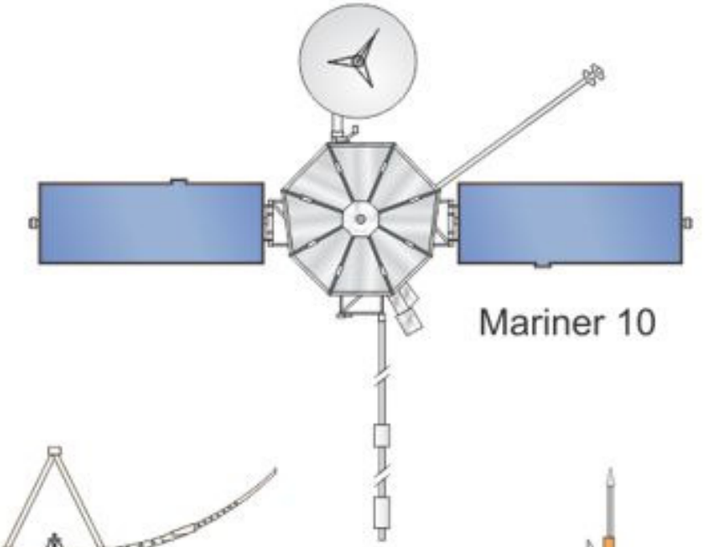
# Exploration of Venus

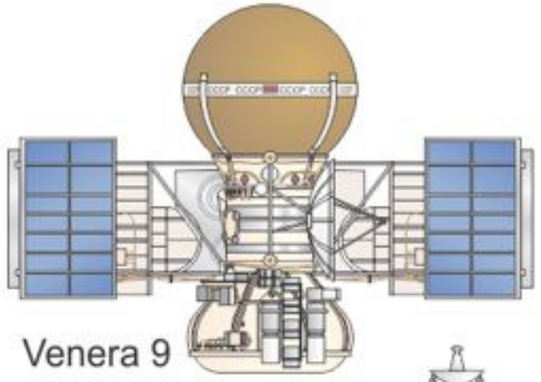

Venera 1

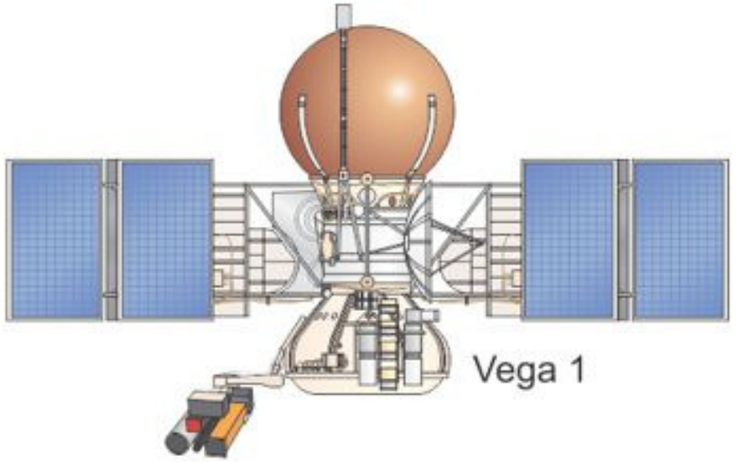
Venera 4

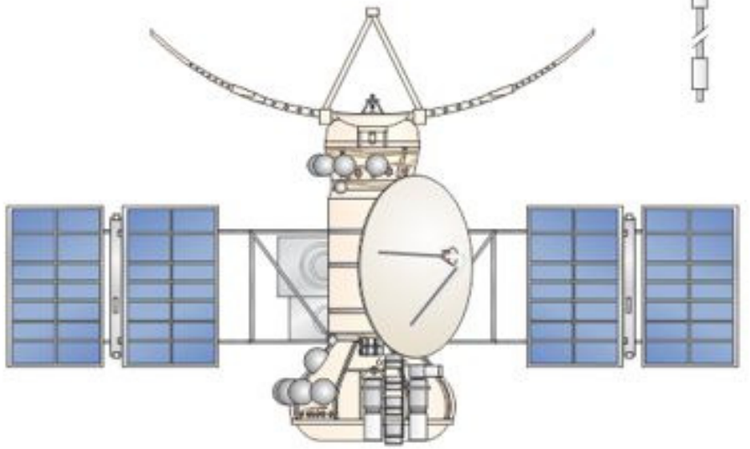

Mariner 2

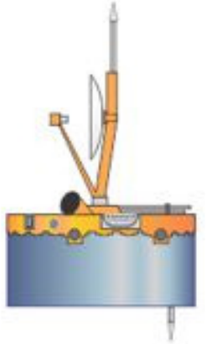

Mariner 5

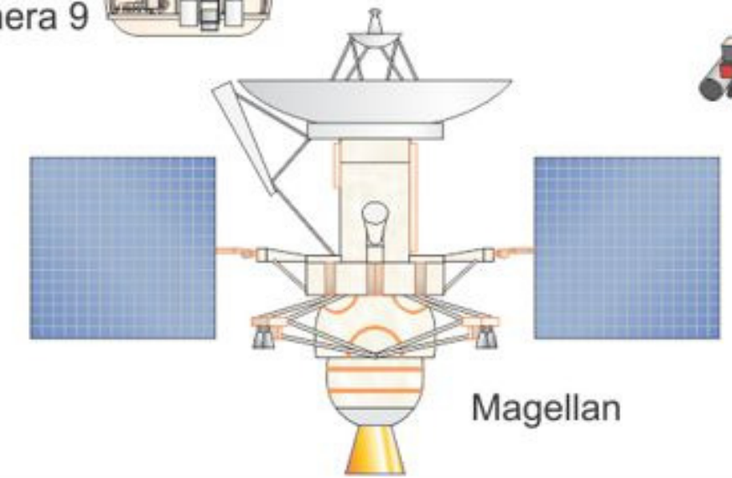

Mariner 10

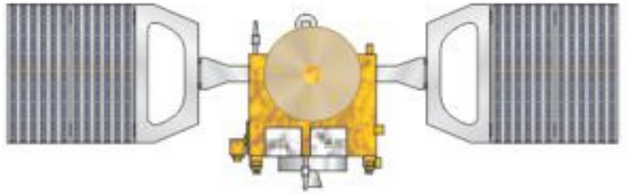

Venera 9

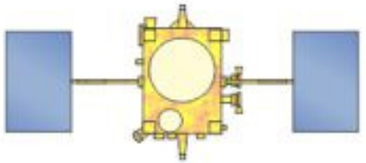

Vega 1


Venera 15

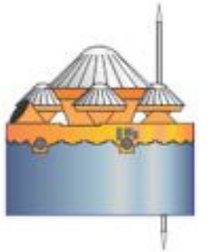

Pioneer 12


Magellan


Venus Express

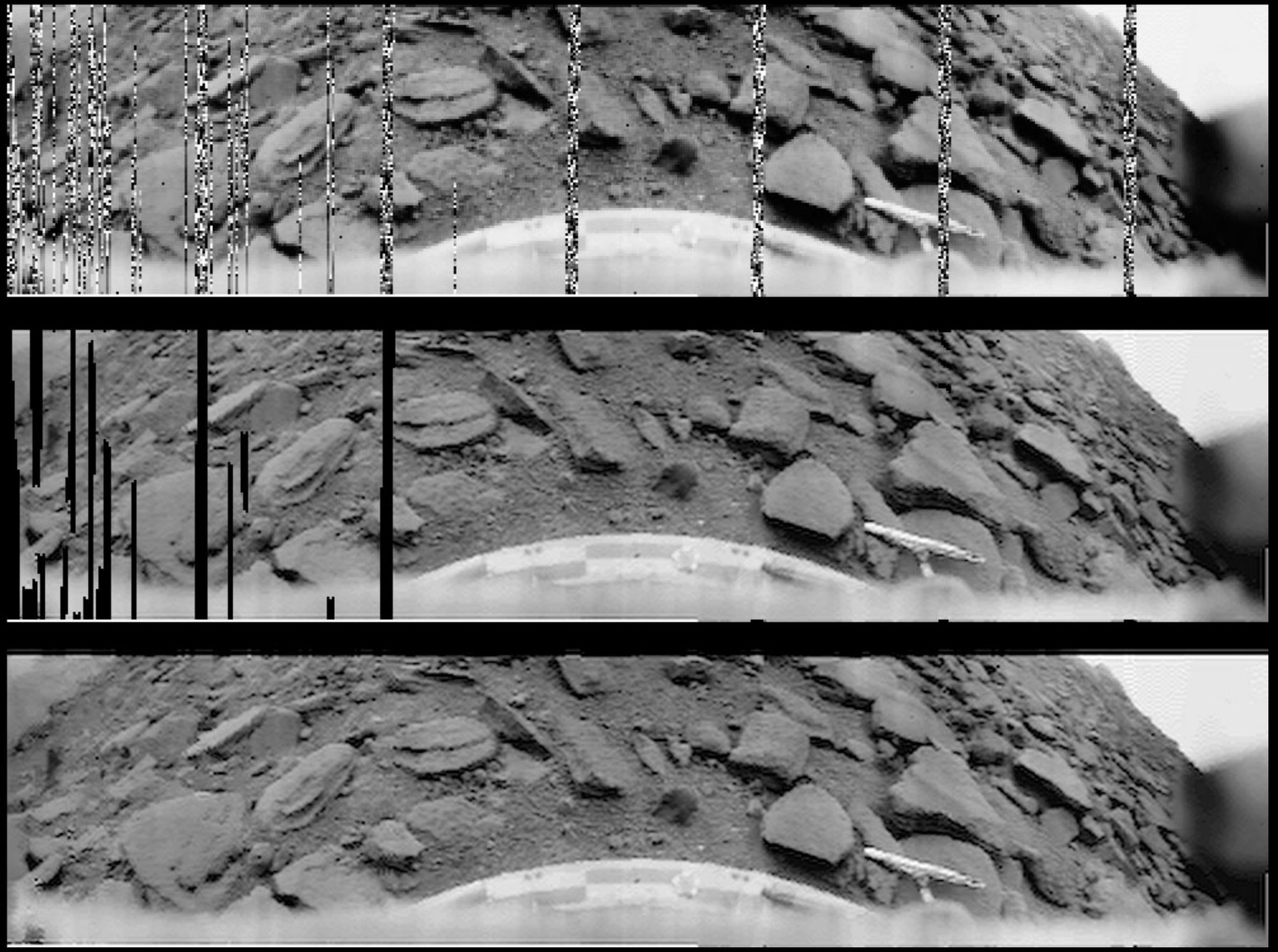

Akatsuki
Venus Climate Orbiter


Astronaut for scale reference


Pioneer 13

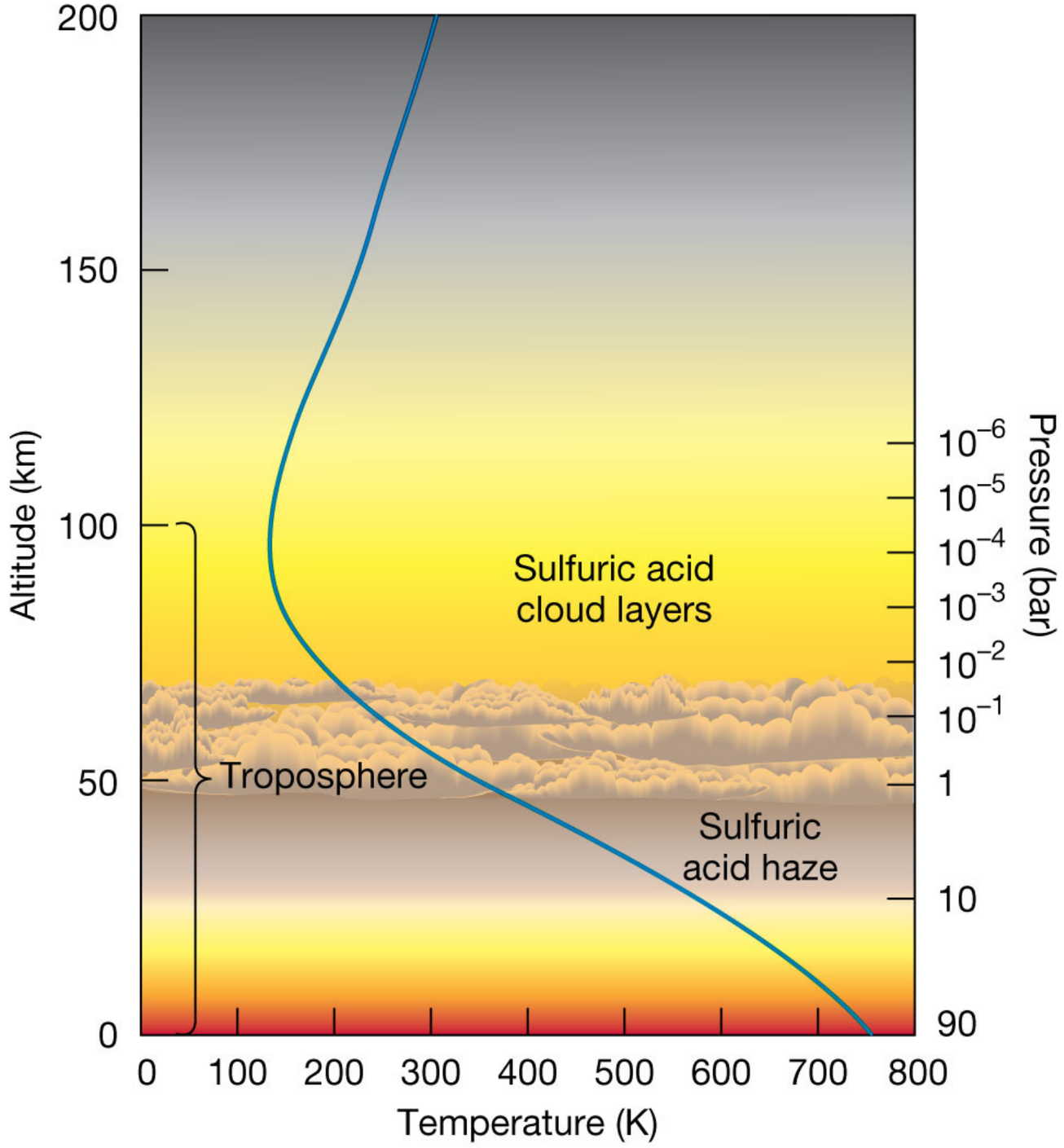
HistoricSpacecraft.com

# Venera 9 (1975)



# Venera 13 (1982)

***“If Venus did not exist in our solar system, we would not dare to imagine it” - Francois Forget***





- **Primarily carbon dioxide (96.5%) and nitrogen (3.5%) atmosphere with sulfuric acid haze.**

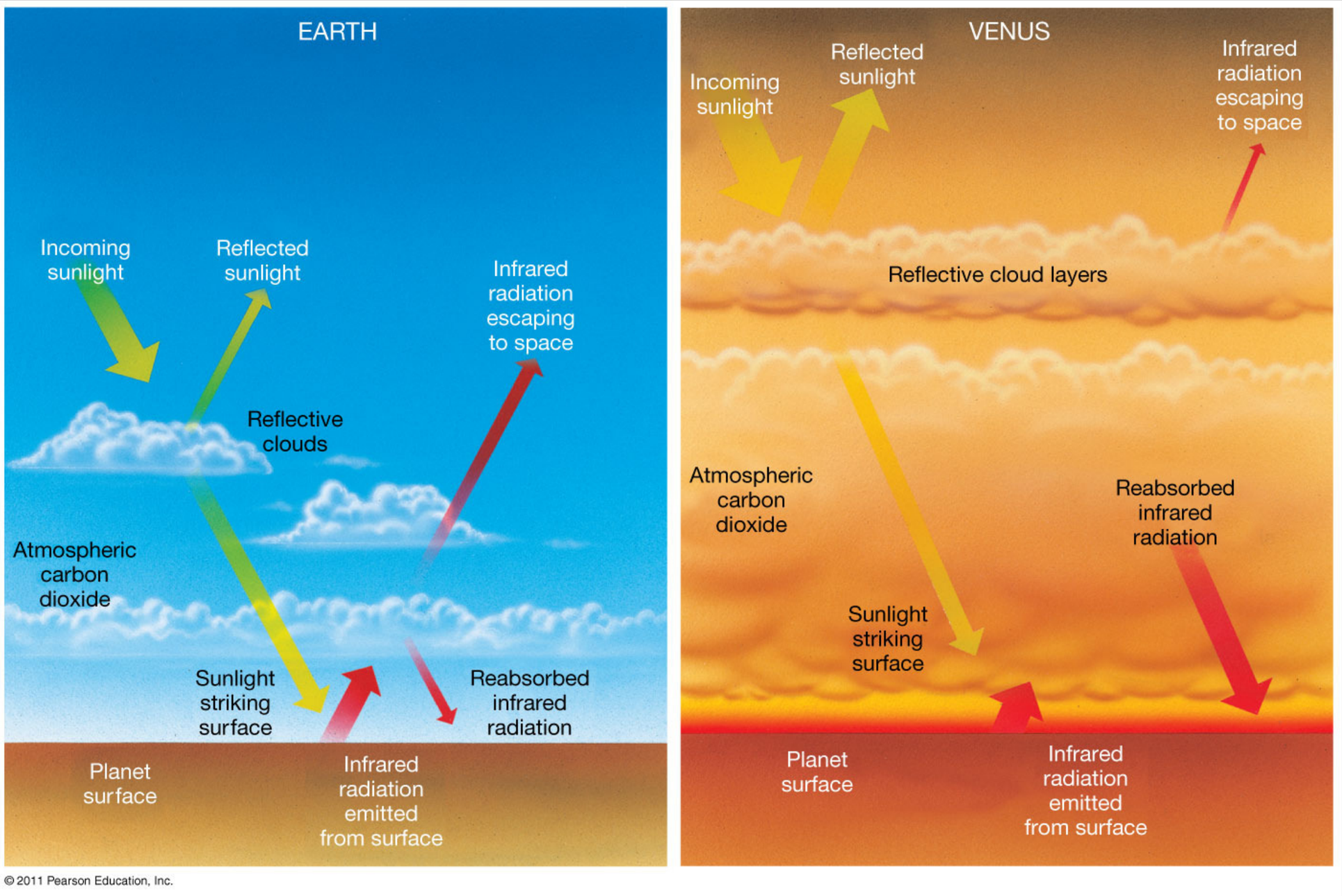
- **Surface temperature**
  **= 462 degrees C**
  **= 864 degrees F**

- **Surface pressure is 92 times the surface pressure of Earth.**

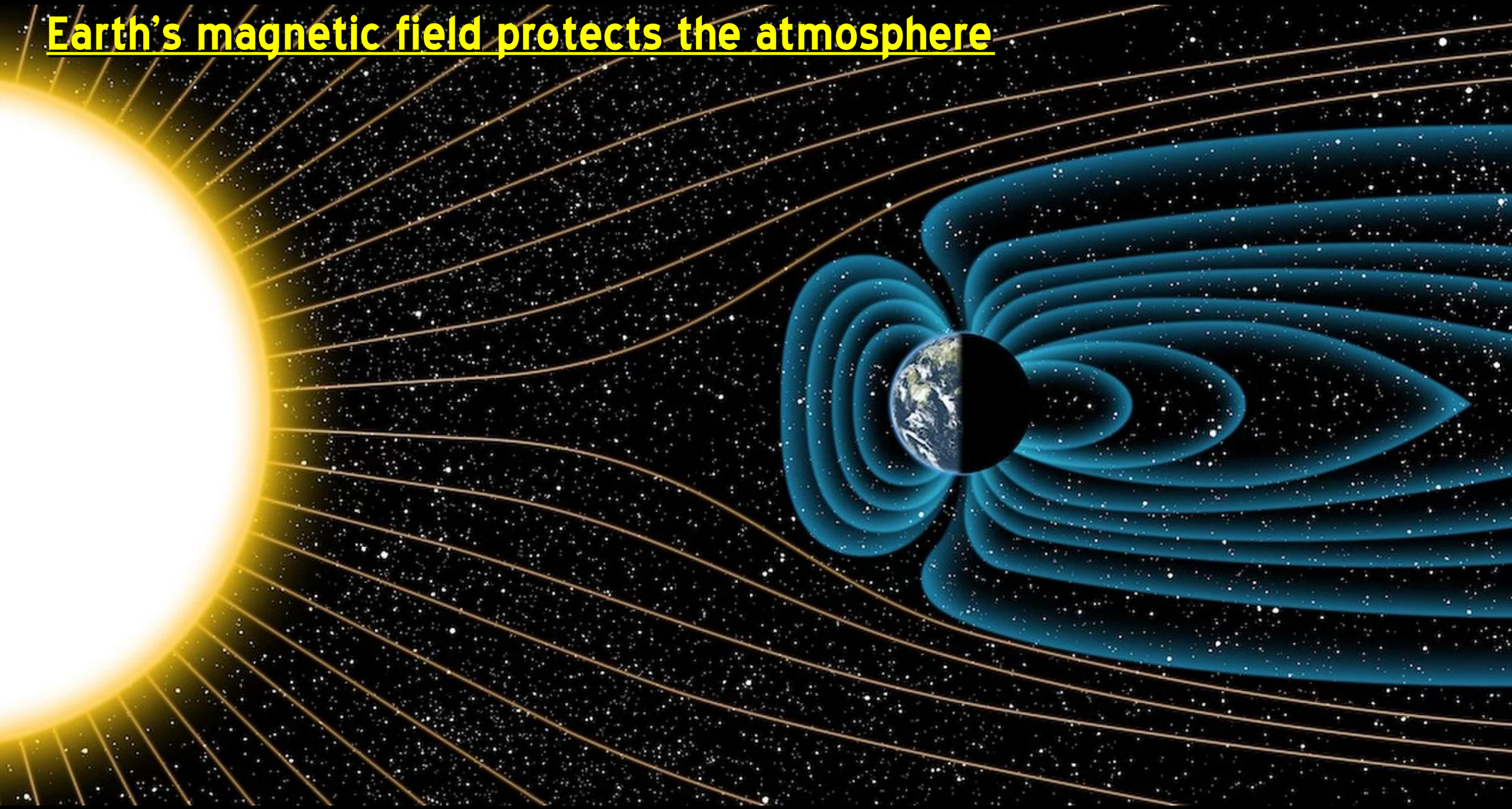
- **Atmosphere is extremely dry!**

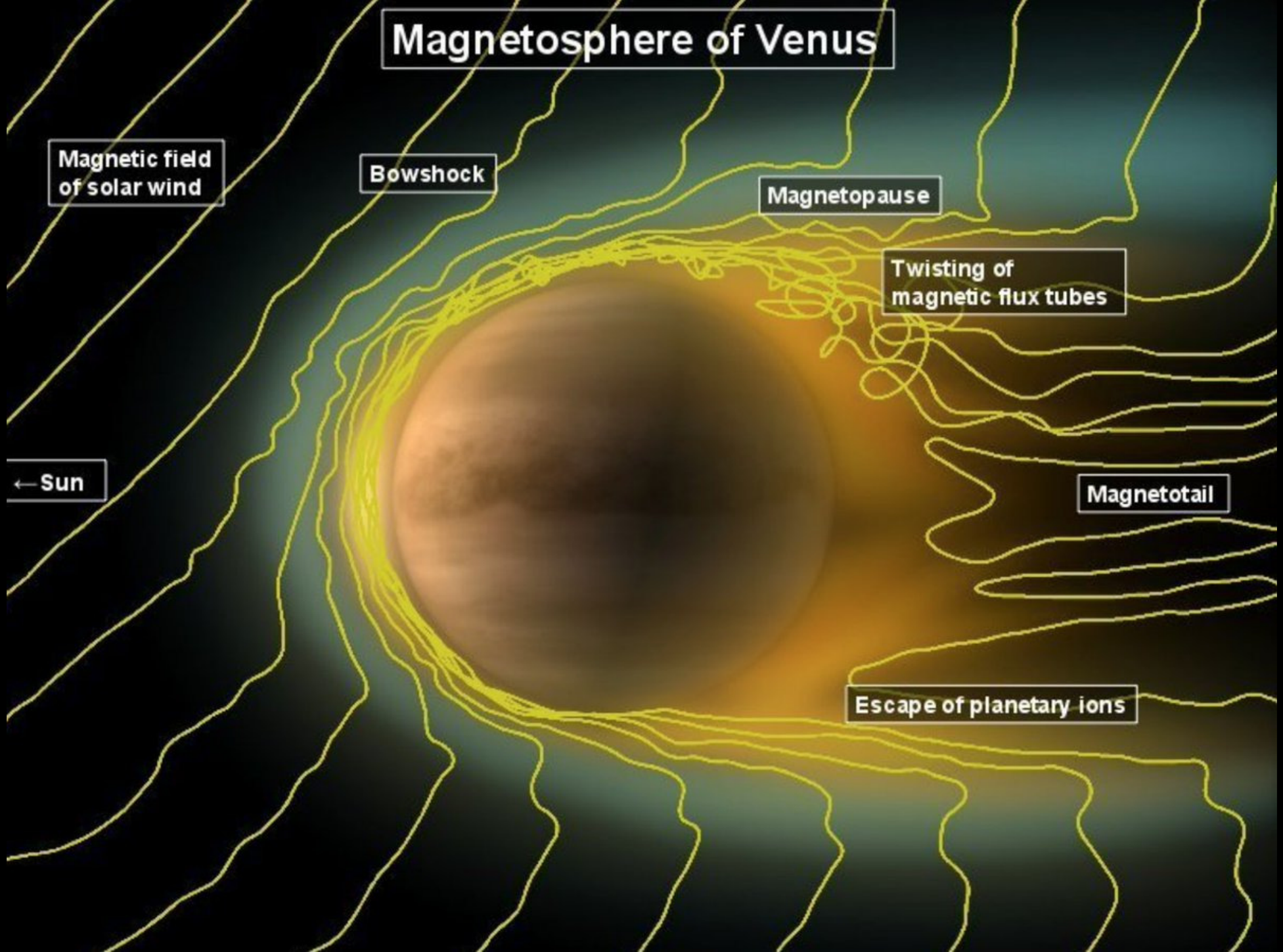
- **Deuterium abundance in the atmosphere is ~100 times higher than Earth.**

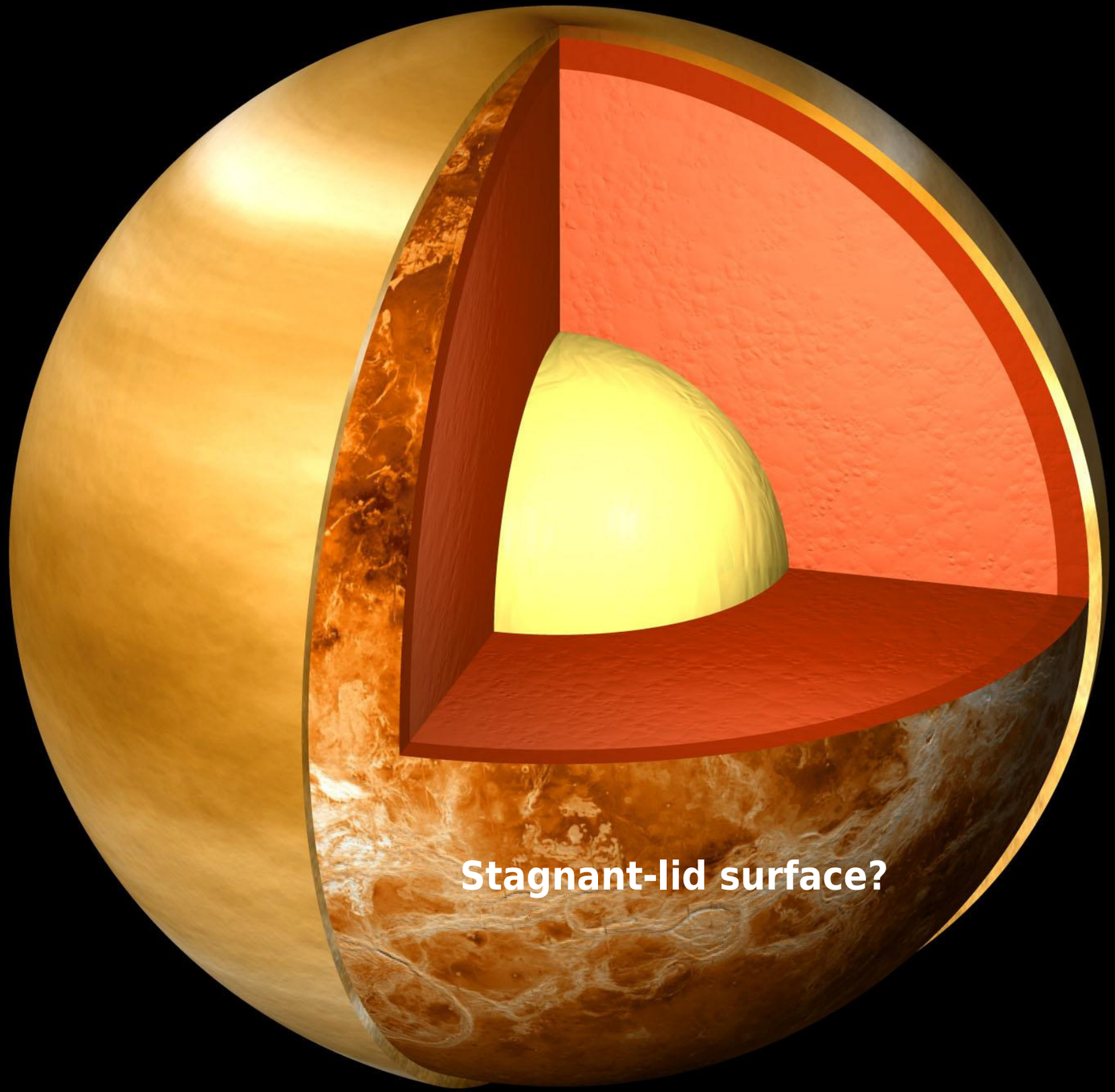
# Venus Atmosphere: Runaway Greenhouse



# Earth's magnetic field protects the atmosphere



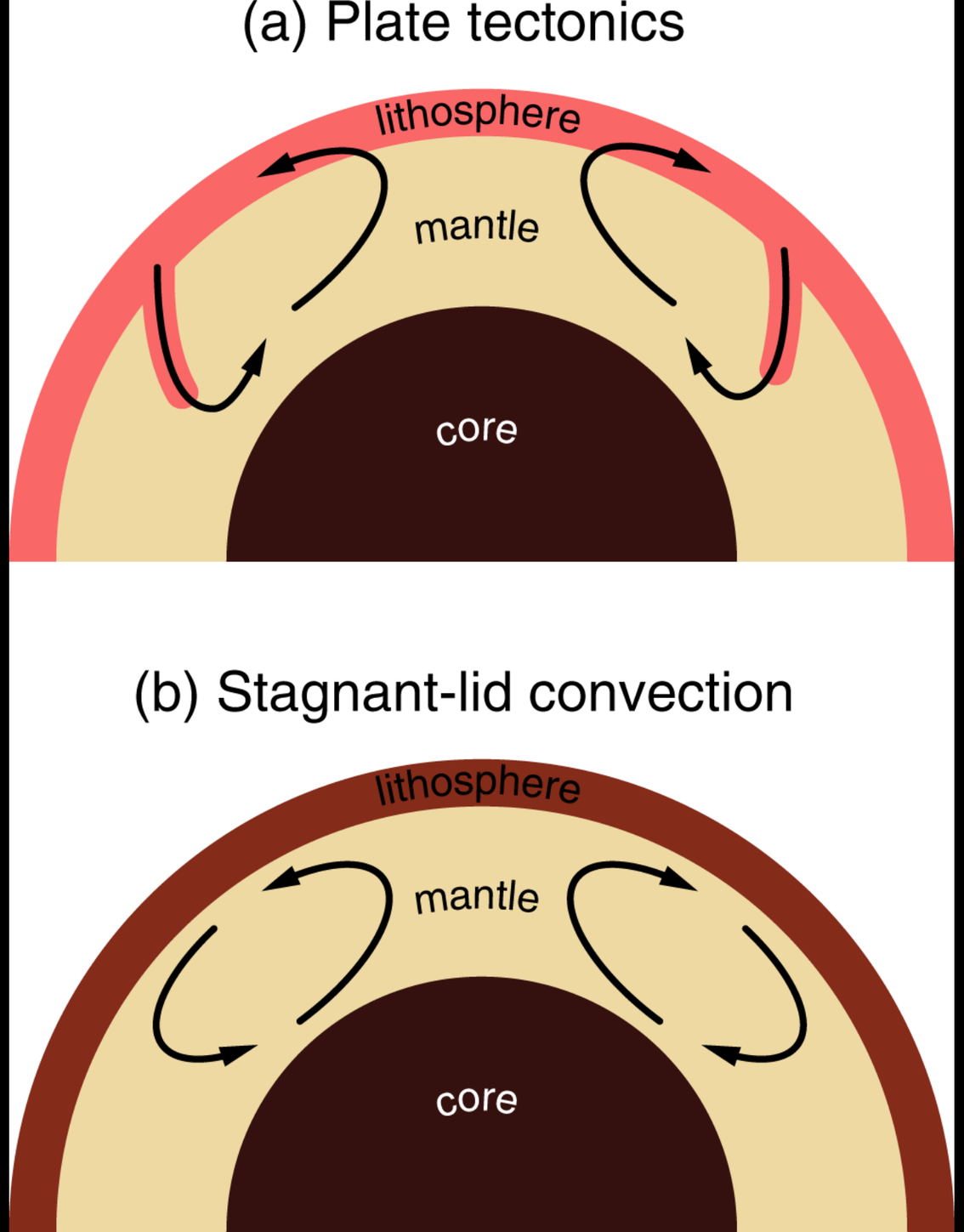

Magnetosphere of Venus
Magnetic field of solar wind
Bowshock
Magnetopause
Twisting of magnetic flux tubes
←Sun
Magnetotail
Escape of planetary ions


Stagnant-lid surface?

- **Earth has plate tectonics that recycles the crust and exchanges material between interior and surface.**

- **Venus may have a stagnant-lid, so interaction between the interior and surface is greatly reduced.**

- **Outgassing (volcanism) is a critical component of atmospheric recycling.**

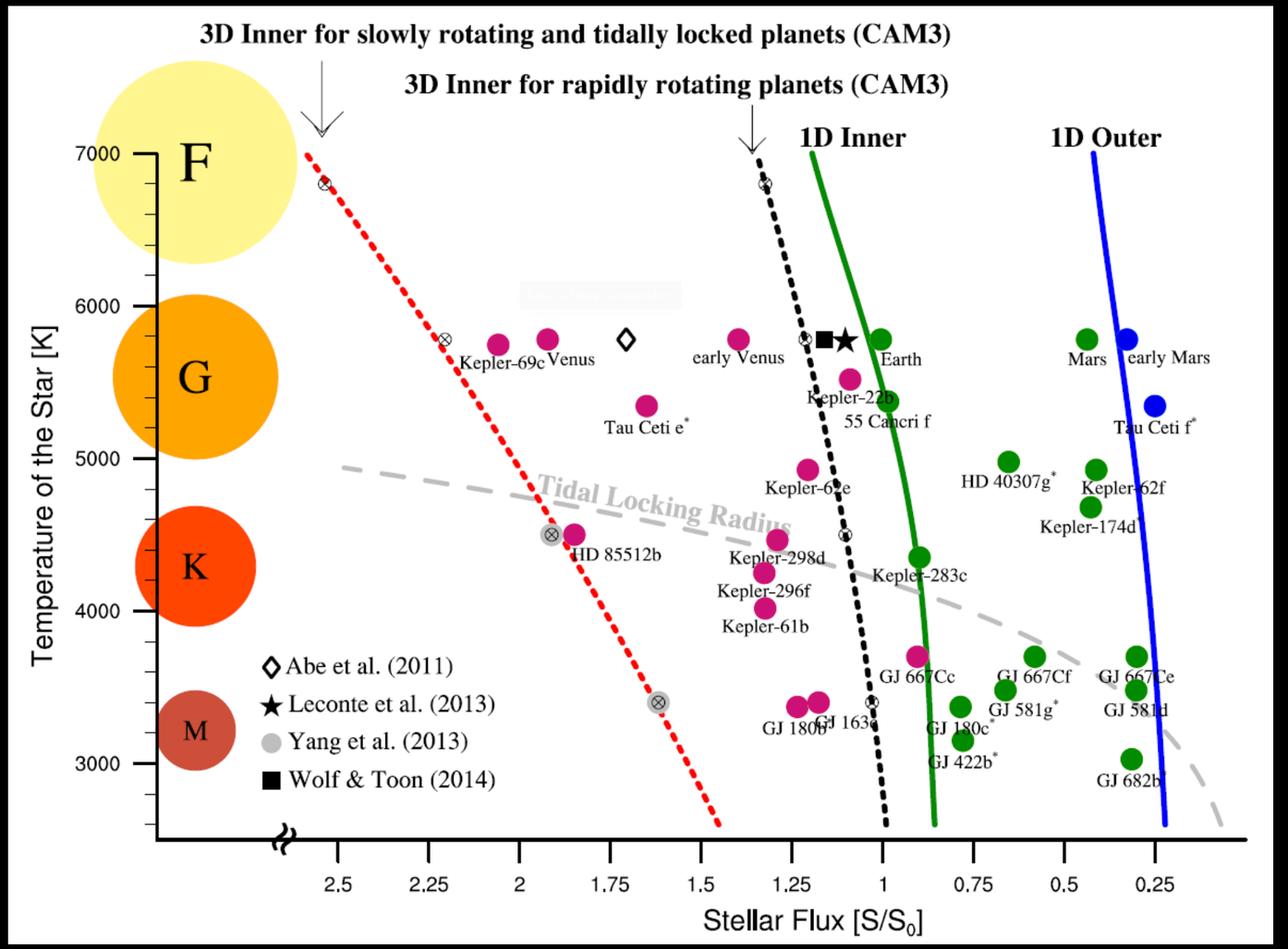



• Herrick & Hensley, “Surface changes observed on a Venusian volcano during the Magellan mission”, 2023, Science, 379, 1205

• Hahn & Byrne, “A Morphological and Spatial Analysis of Volcanoes on Venus”, 2023, Journal of Geophysical Research: Planets, 128, e2023JE007753

• Sulcanese et al. “Evidence of ongoing volcanic activity on Venus revealed by Magellan radar”, 2024, Nature Astronomy, 8, 973

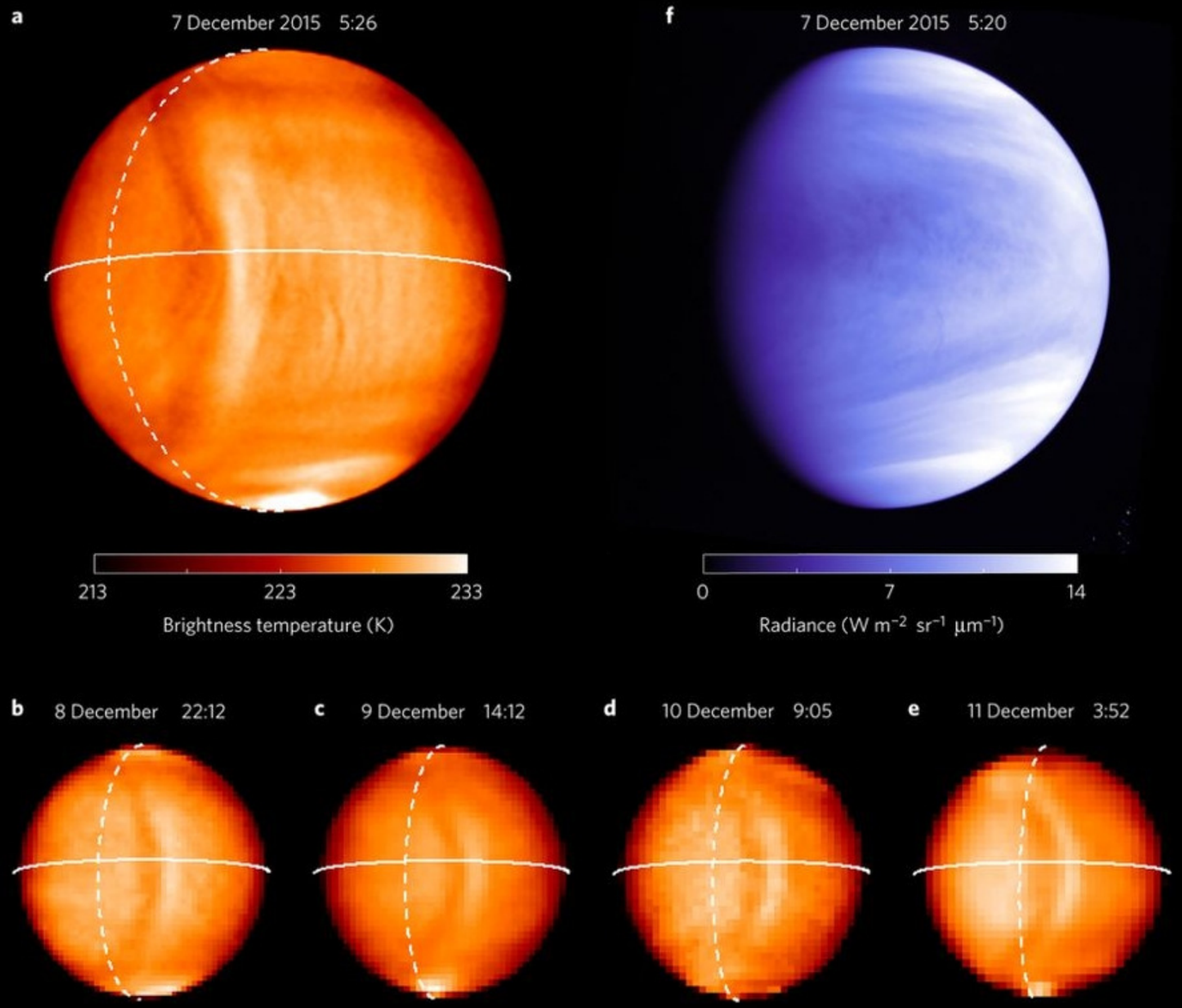
# Tidal locking: time scale




**Many planets, particularly those orbiting M dwarfs, are assumed to be tidally locked. For comparison, the tidal locking time scale for Venus is $6.5\times10^6$ years.**

Yang et al. 2014, ApJ, 787, L2
Kane. 2022, Nature Astronomy, 6, 420

# Tidal locking: climate effects

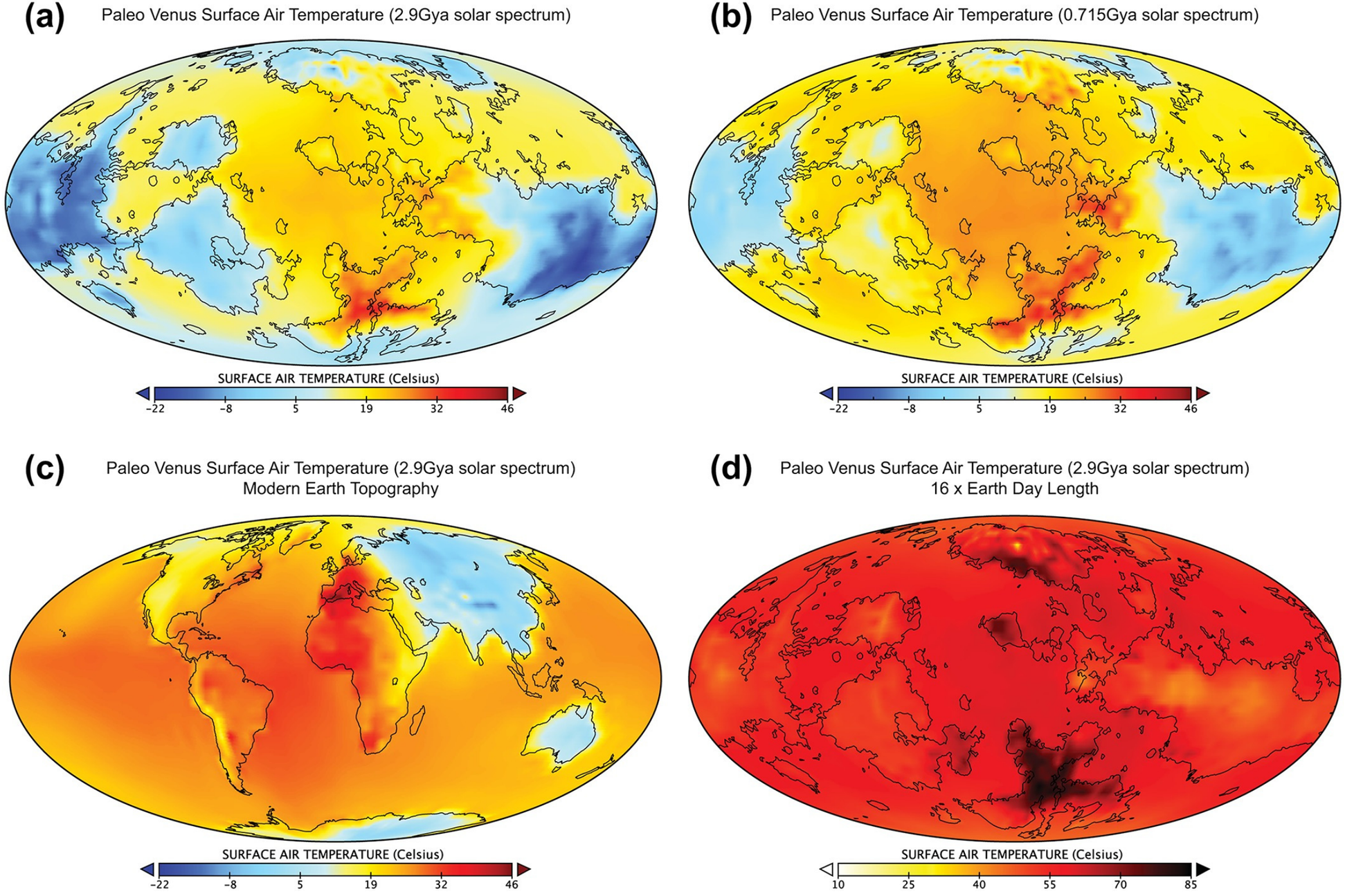



- The atmosphere of Venus is ~2 orders of magnitude more massive than that of Earth's atmosphere.

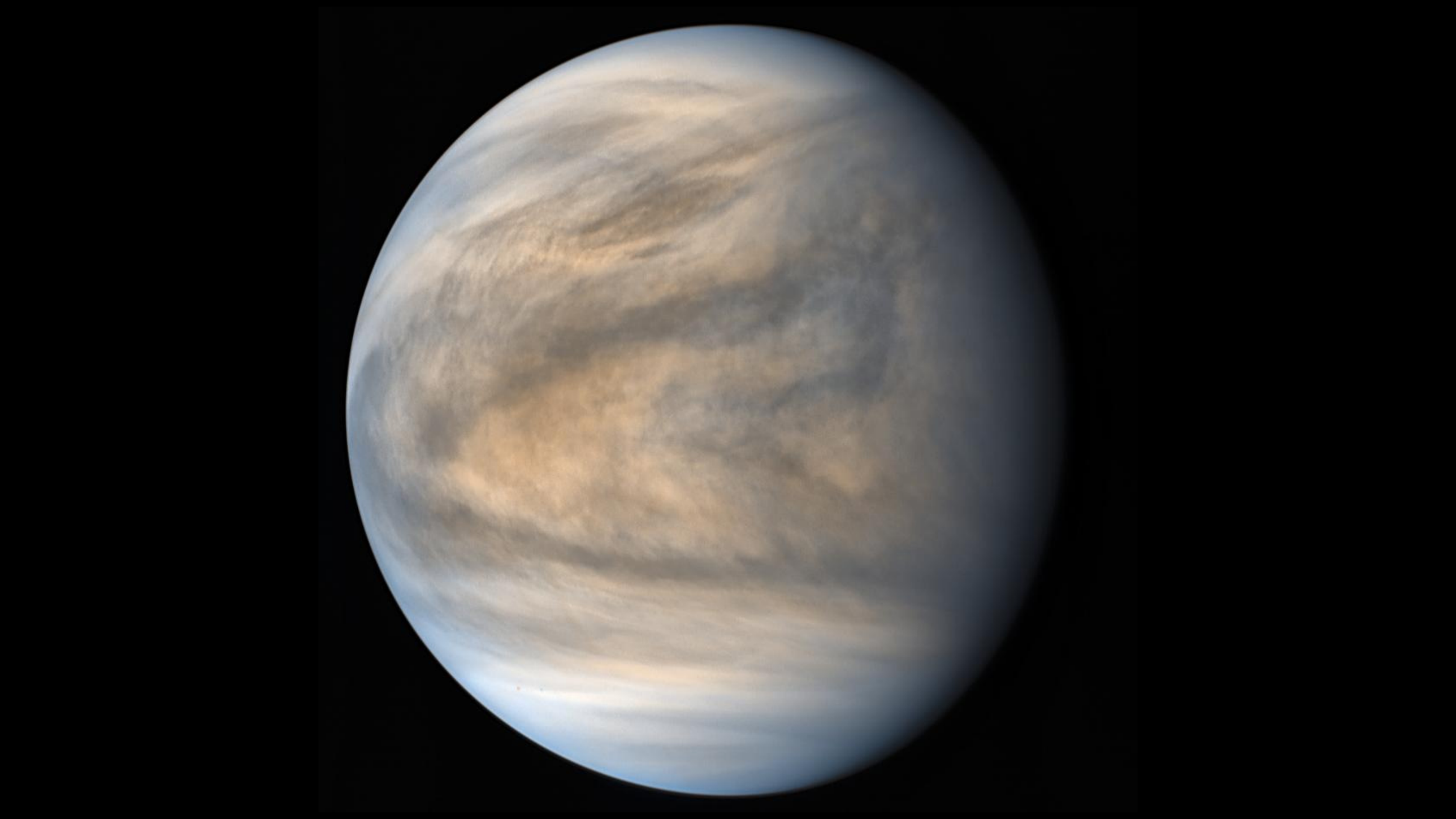
- Approximately 3% of sunlight incident at the top of the Venusian atmosphere reaches the surface. Thus, almost all of the solar energy absorbed by the planet is deposited into the atmosphere.

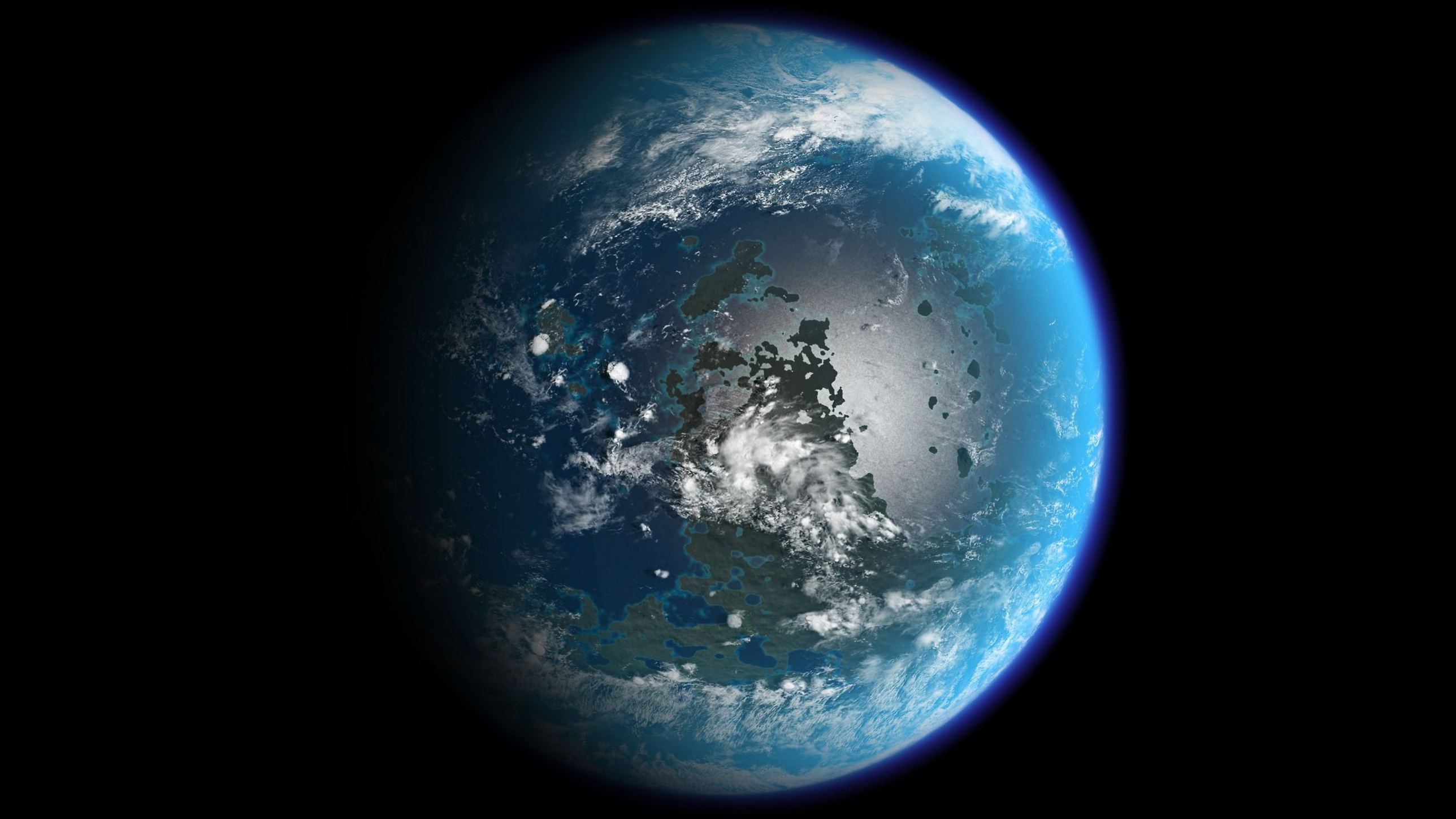
- This, in turn, produces a turbulent atmosphere with a dramatic velocity gradient (super-rotation), that interacts strongly with the surface topography. Such interactions can transfer angular momentum between the atmosphere and solid planet.


Fukuhara et al. 2017, Nature Geoscience, 10, 85
Margot et al. 2021, Nature Astronomy, 5, 676
Kane. 2022, Nature Astronomy, 6, 420




- **Way et al. “Was Venus the first habitable world of our solar system”, 2016, Geophysical Research Letters, 43, 8376**
- **Turbet et al. “Day-night cloud asymmetry prevents early oceans on Venus but not on Earth”, Nature, 598, 276**





# Venus: Evolutionary Factors

- What is the interior structure and composition of Venus (Margot et al. 2021)? How much does it differ from the Earth and the Sun?

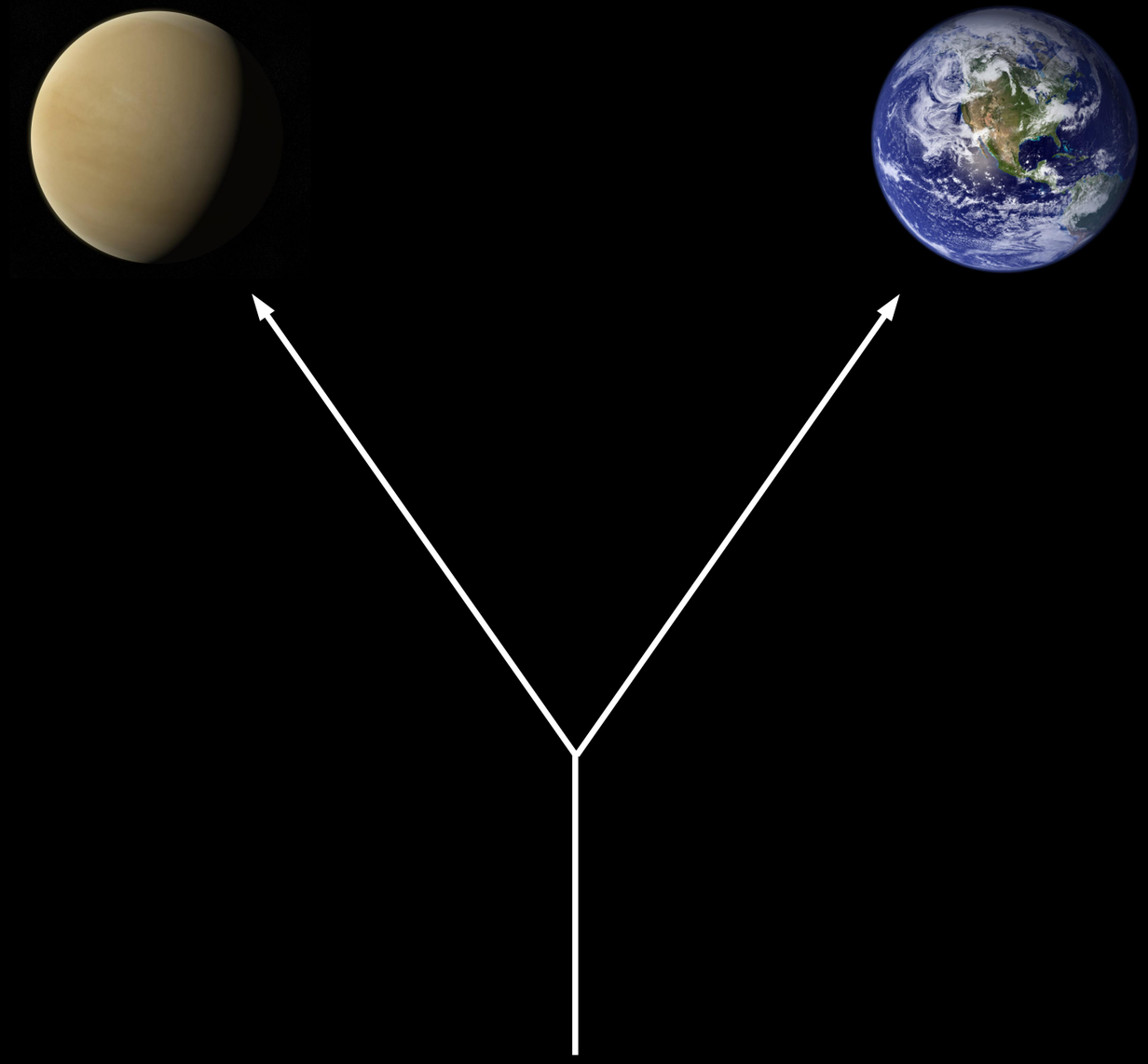
- What has been the history of tectonics, volatile cycling, and volcanic resurfacing (Ivanov & Head 2011)? Does any subduction occur today (Smrekar et al. 2018; Byrne et al. 2021)?

- What is the detailed composition and atmospheric chemistry that exists within the Venusian middle and deep atmosphere and how does it interact with the surface?

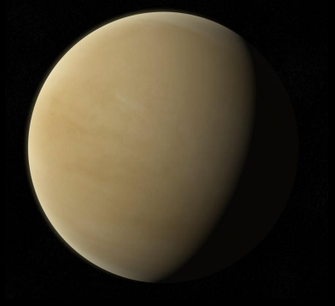
- Where did the water go (Kane et al. 2020)? Was hydrogen loss and abiotic oxygen production prevalent, or did surface hydration dominate?

- Did Venus have a habitable period (Way et al. 2016)? That is, did Venus ever cool after formation (Hamano et al. 2013; Turbet et al. 2021)? If Venus had a habitable period, how long did it last (Kane et al. 2019)?

- What are the major factors that have caused a divergence in the evolutionary history of Venus and Earth (insolation flux, rotation, volatile inventory, surface subduction, lack of a significant moon, etc)?



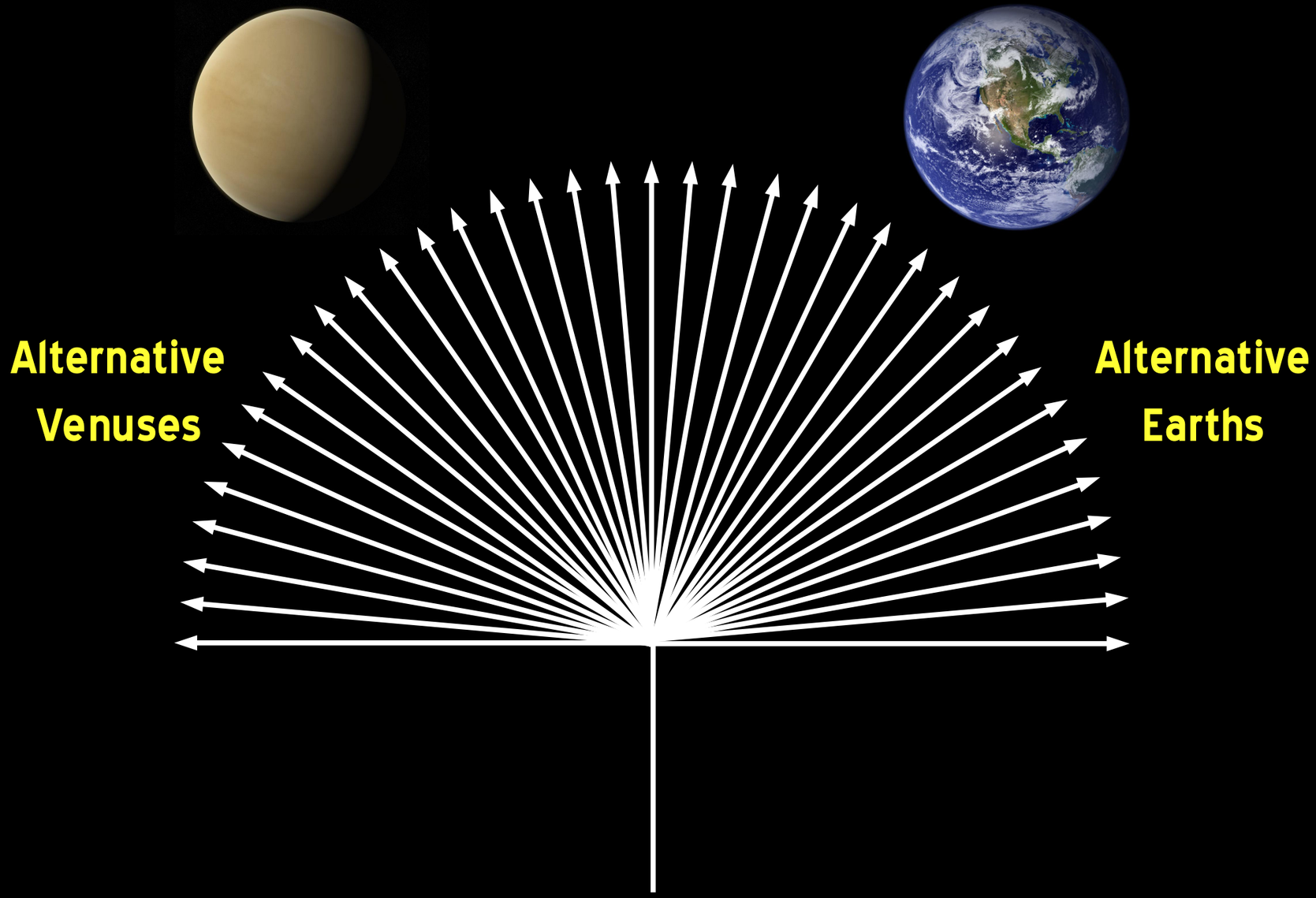
Starting Conditions



What caused the divergence between Venus and Earth?

Increasing luminosity of the Sun?
Loss of plate tectonics?
Decreasing magnetic field?
Slow rotation?
A combination of these, or something else entirely?

# Starting Conditions


Alternative
Venuses
Alternative
Earths
Starting Conditions

**Two-pronged solution:**

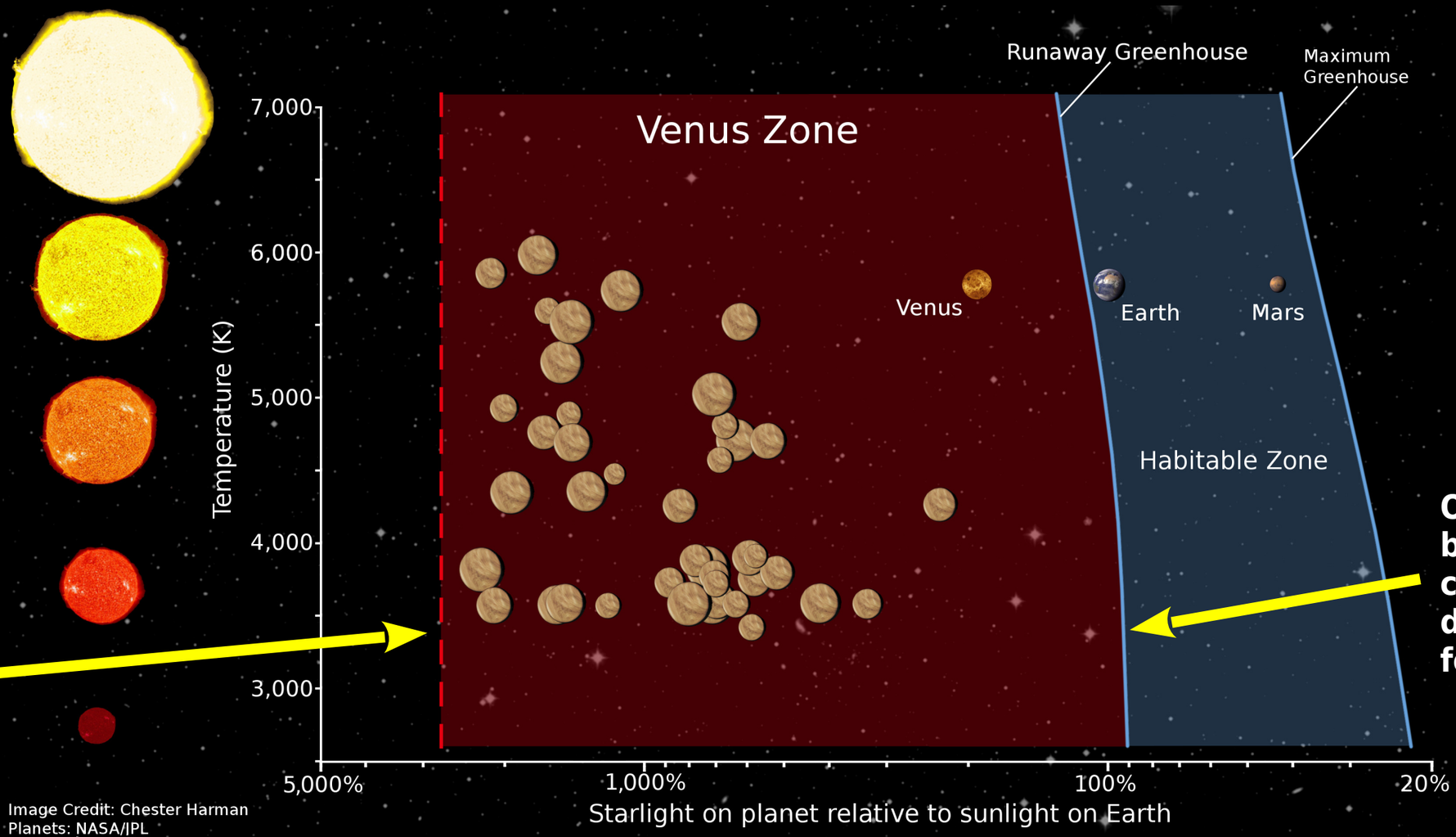
**The statistics of exoplanets**

**The evolutionary history of Venus**

**Planetary habitability**

# A Catalog of Potential Venus Analogs

**Fraction of stars with at least one terrestrial planet within the Venus Zone.**
**For M stars: 32%**
**For GK stars: 45%**
**= Potential Venus analogs are common!**



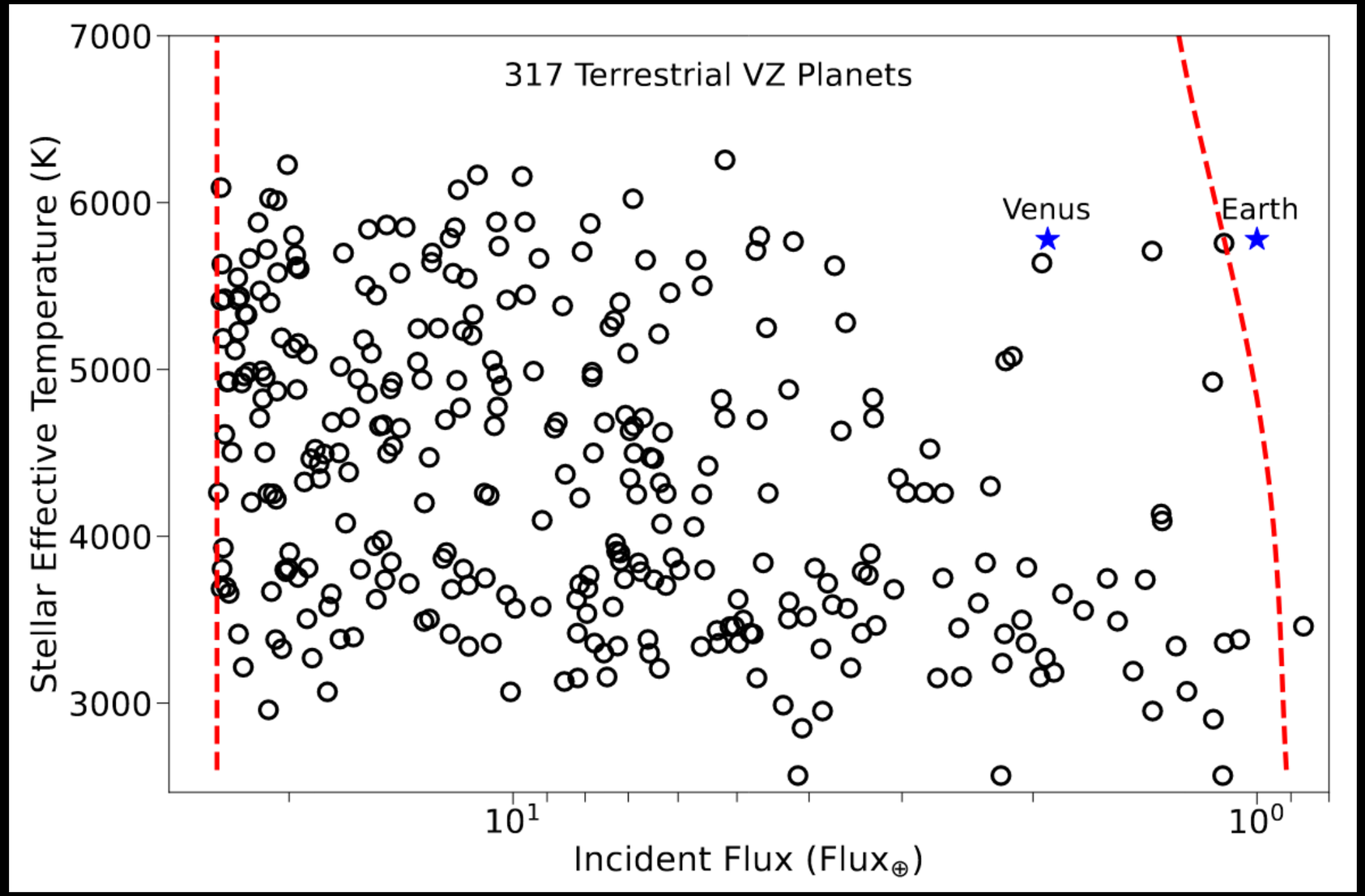

**Inner Venus Zone boundary = 25x stellar flux, based upon “cosmic shoreline”.**

**Outer Venus Zone boundary is conservative and does not account for slow rotators.**

Image Credit: Chester Harman
Planets: NASA/JPL

Kane, Kopparapu, Domagal-Goldman. 2014, ApJ, 794, L5

# A Catalog of Potential Venus Analogs



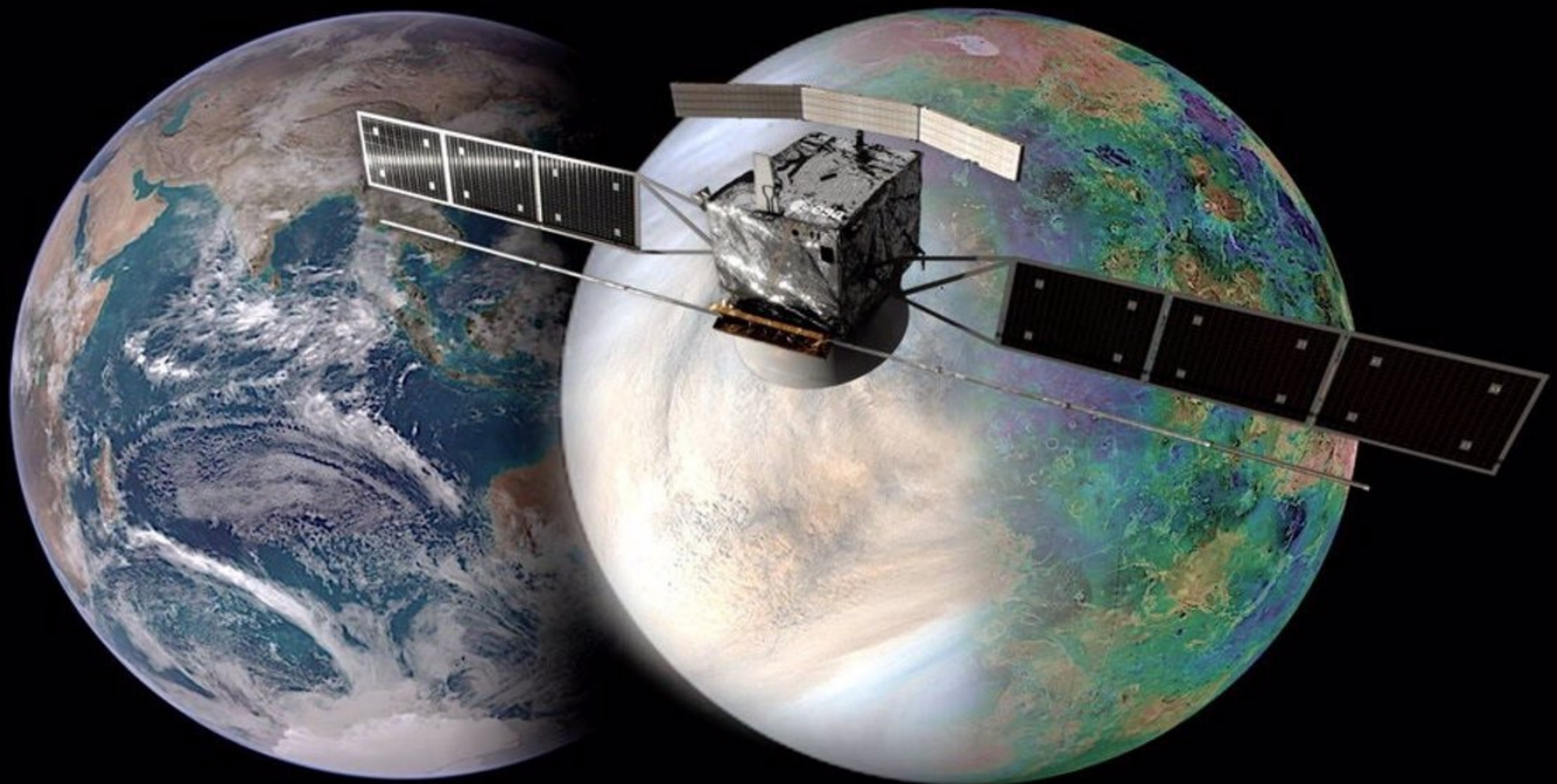

**We have produced a catalog of exoVenus candidates, including measured/derived parameters, climate simulations, and spectra.**

Ostberg & Kane, 2019, AJ, 158, 195; Ostberg et al. 2023, AJ, 165, 168

**Two NASA Venus missions selected as Discovery class planetary missions. Current anticipated launches are 2030/2031.**


**The missions are complementary: DAVINCI will study the atmosphere, whilst VERITAS will investigate the surface and interior. Both aspects are critical pieces of the habitability and evolution narrative.**

**The European Space Agency (ESA) has selected EnVision as a medium-class planetary probe. Expected launch is early 2030s.**



**EnVision will be an orbiter that maps the surface, with particular attention to the “tesserae”, revealing basaltic versus granitic compositions, indicative of past surface water.**

# Venus as an exoplanet/habitability laboratory

1. Terrestrial planets are extremely common, and studying their atmospheres will teach us how common Venus-like planets really are. We will never have in-situ data for an exoplanet. Surface conditions will always be inferred from models based on solar system data.

2. Venus is compliciated, with many differences from Earth! For example, Venus is not tidally locked, likely due to interactions of the massive atmosphere and dynamical climate with the surface. Venus is also still volcanically active and contributing to its present atmosphere!

3. The possibility of a past "wet" Venus presents clues to first-order habitability factors: **planetary rotation rate**, **atmospheric carbon sequestration (plate tectonics)**, and **instellation flux**.

4. **Near-term opportunities:** numerous JWST Cycle 1/2 GO targets that may be Venus analogs, including TRAPPIST-1 c, GJ 1132 b, and L 98-59 b. $CO_2$ absorption features at 2.7 and 4.3 μm, though degeneracy with Earth-similar atmospheric compositions persist.

**Mid-term opportunities:** Venus missions, including DAVINCI (atmospheric probe), VERITAS (surface and interior), and EnVision (surface geology). These provide critical geology-atmosphere-chemistry models during JWST continued operations. The ESA PLATO and Ariel missions will further add to the spectroscopic inventory.

**Long-term opportunities:** Direct imaging (Habitable Worlds Observatory (HWO) and Large Interferometer For Exoplanets (LIFE)), reflectance and emission spectra, and atmospheric rotation rates will provide critical diagnostics. Extending spectral coverage into the UV will cover ozone absorption.

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