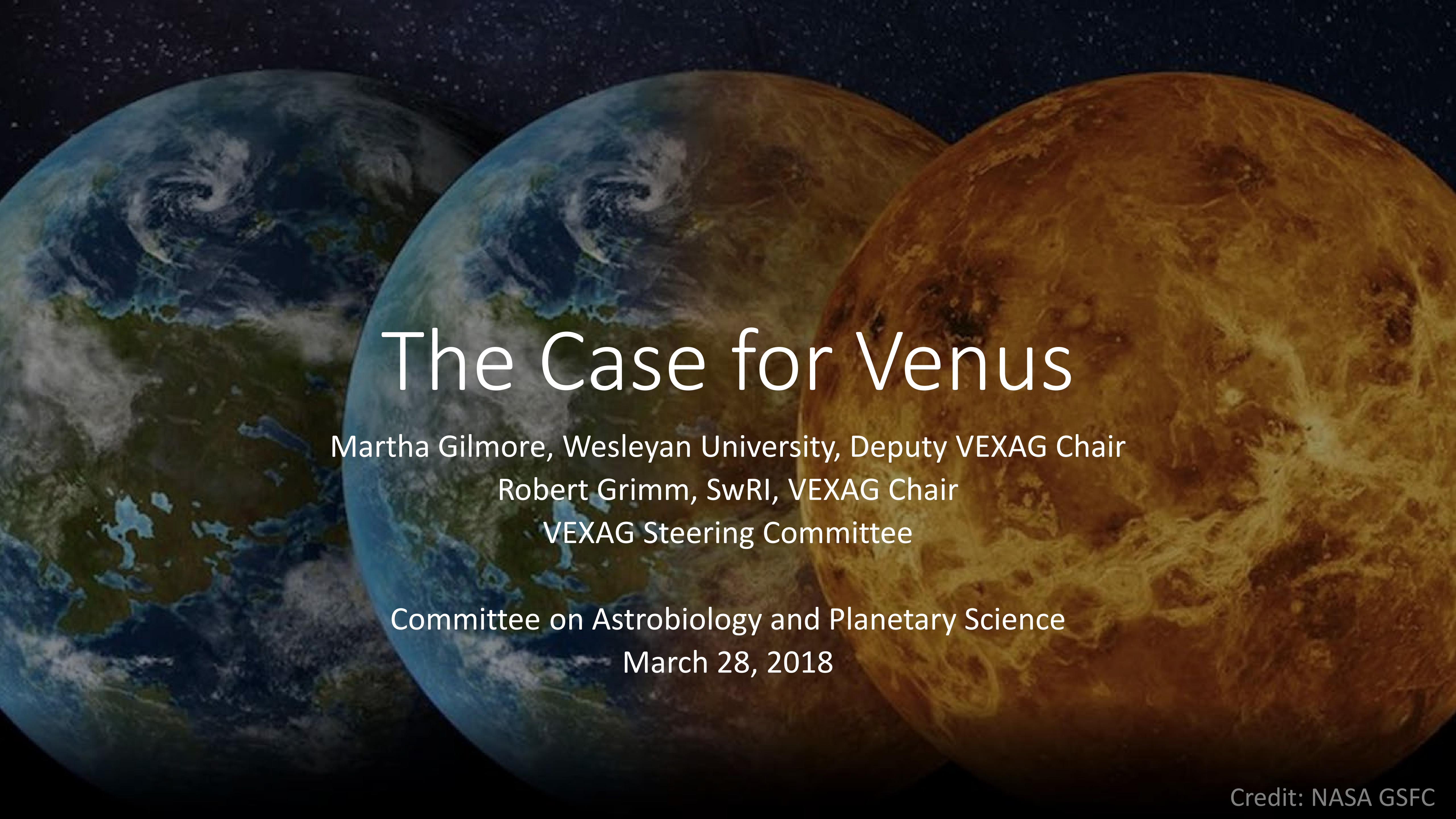

The Case for Venus

Martha Gilmore, Wesleyan University, Deputy VEXAG Chair
Robert Grimm, SwRI, VEXAG Chair
VEXAG Steering Committee

Committee on Astrobiology and Planetary Science
March 28, 2018

Credit: NASA GSFC

VEXAG Steering Committee

Robert Grimm (Southwest Research Institute), Chair

Martha Gilmore (Wesleyan University), Deputy Chair

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Lynn Carter (Univ. Arizona)

James Cutts (JPL), Roadmap Focus Group Lead

Candace Gray (NM State U.) Early-Career Rep.

Gary Hunter (NASA GRC), Technol. Focus Group Lead

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Joseph O'Rourke (ASU), Early-Career Rep.

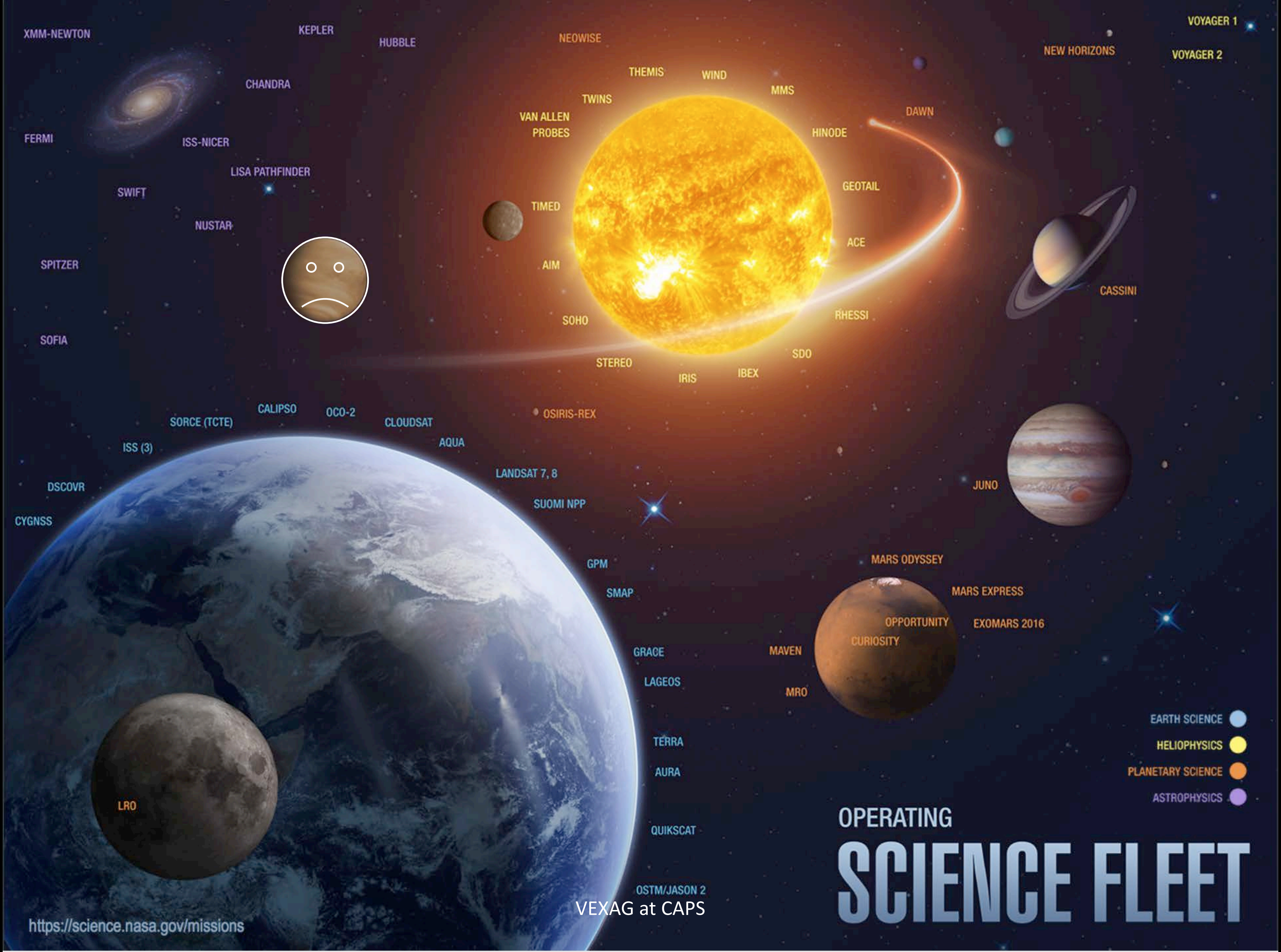
Paul Steffes (Georgia Tech. University)

Allan Treiman (Lunar & Planetary Institute), Goals, Objectives, and Investigations Lead

Constantine Tsang (Southwest Research Institute)

Tommy Thompson (JPL), Scribe

Adriana Ocampo (NASA HQ) ex officio


XMM-NEWTON
KEPLER
HUBBLE
CHANDRA
FERMI
ISS-NICER
LISA PATHFINDER
SWIFT
NUSTAR
SPITZER
SOFIA
NEOWISE
THEMIS
WIND
MMS
TWINS
VAN ALLEN PROBES
HINODE
DAWN
TIMED
GEOTAIL
ACE
AIM
SOHO
RHESSI
SDO
STEREO
IRIS
IBEX
NEW HORIZONS
VOYAGER 1
VOYAGER 2
CASSINI
JUNO
OSIRIS-REX
SORCE (TCTE)
CALIPSO
OCO-2
CLOUDSAT
AQUA
ISS (3)
LANDSAT 7, 8
SUOMI NPP
DSCOVR
CYGNSS
GPM
SMAP
GRACE
LAGEOS
TERRA
AURA
QUIKSCAT
OSTM/JASON 2
LRO
MARS ODYSSEY
MARS EXPRESS
OPPORTUNITY
EXOMARS 2016
CURIOSITY
MAVEN
MRO
EARTH SCIENCE
HELIOPHYSICS
PLANETARY SCIENCE
ASTROPHYSICS
OPERATING
SCIENCE FLEET
https://science.nasa.gov/missions

Venus Goals, Objectives, and Investigations

Atmosphere

- How did the atmosphere form and evolve?
- What controls the atmospheric super-rotation and greenhouse?
- What is the impact of clouds on climate and habitability?

Surface & Interior

- How is heat released from the interior and has the global geodynamic style changed with time?
- What are the contemporary rates of volcanism and tectonism?
- How did Venus differentiate and evolve over time?

System Interactions & Water

- Was surface water ever present?
- What role has the greenhouse had on climate history?
- How have the interior, surface, and atmosphere interacted as a coupled system over time?

Were Venus and Earth alike, and if so, how and why did they diverge?

Overview

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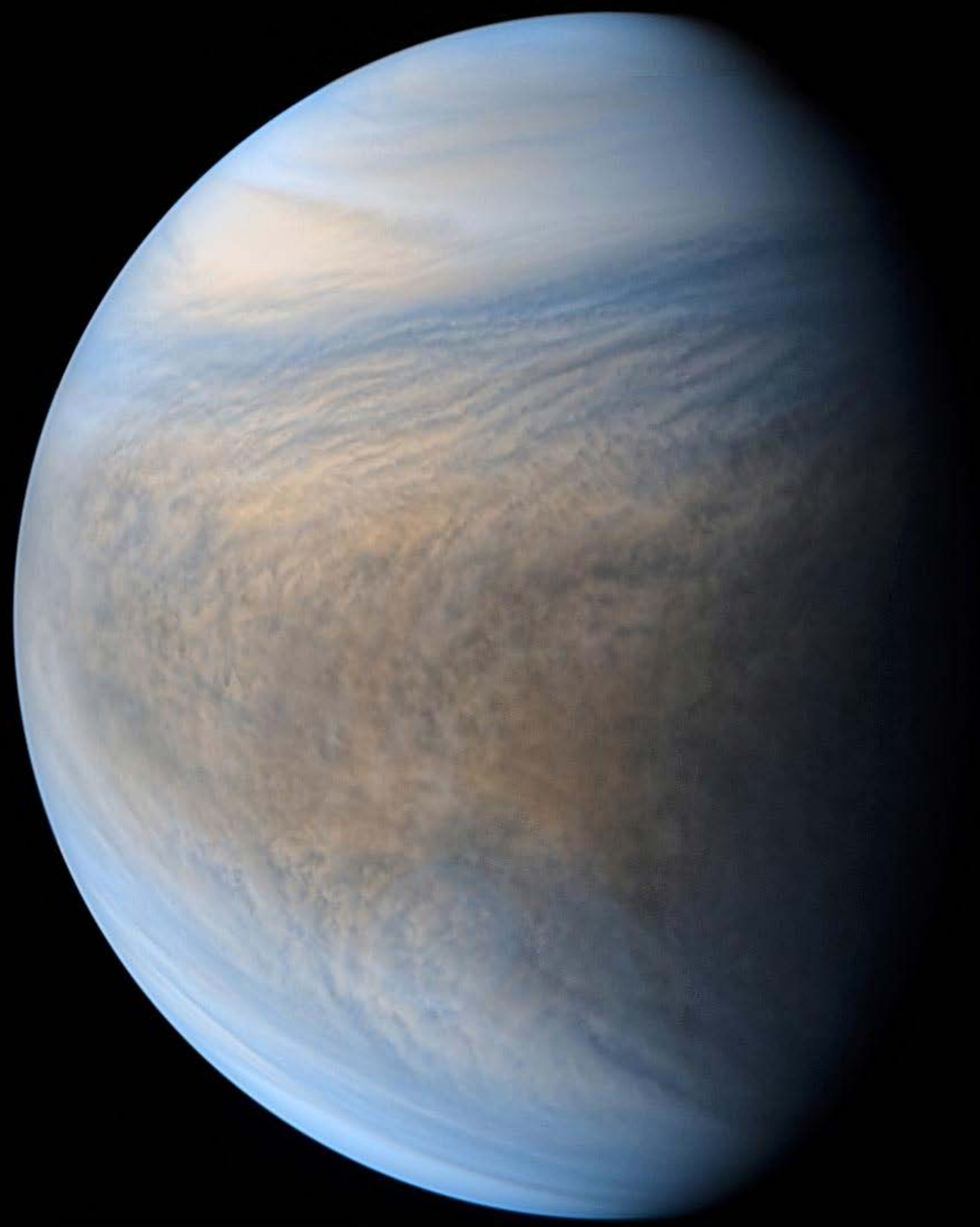
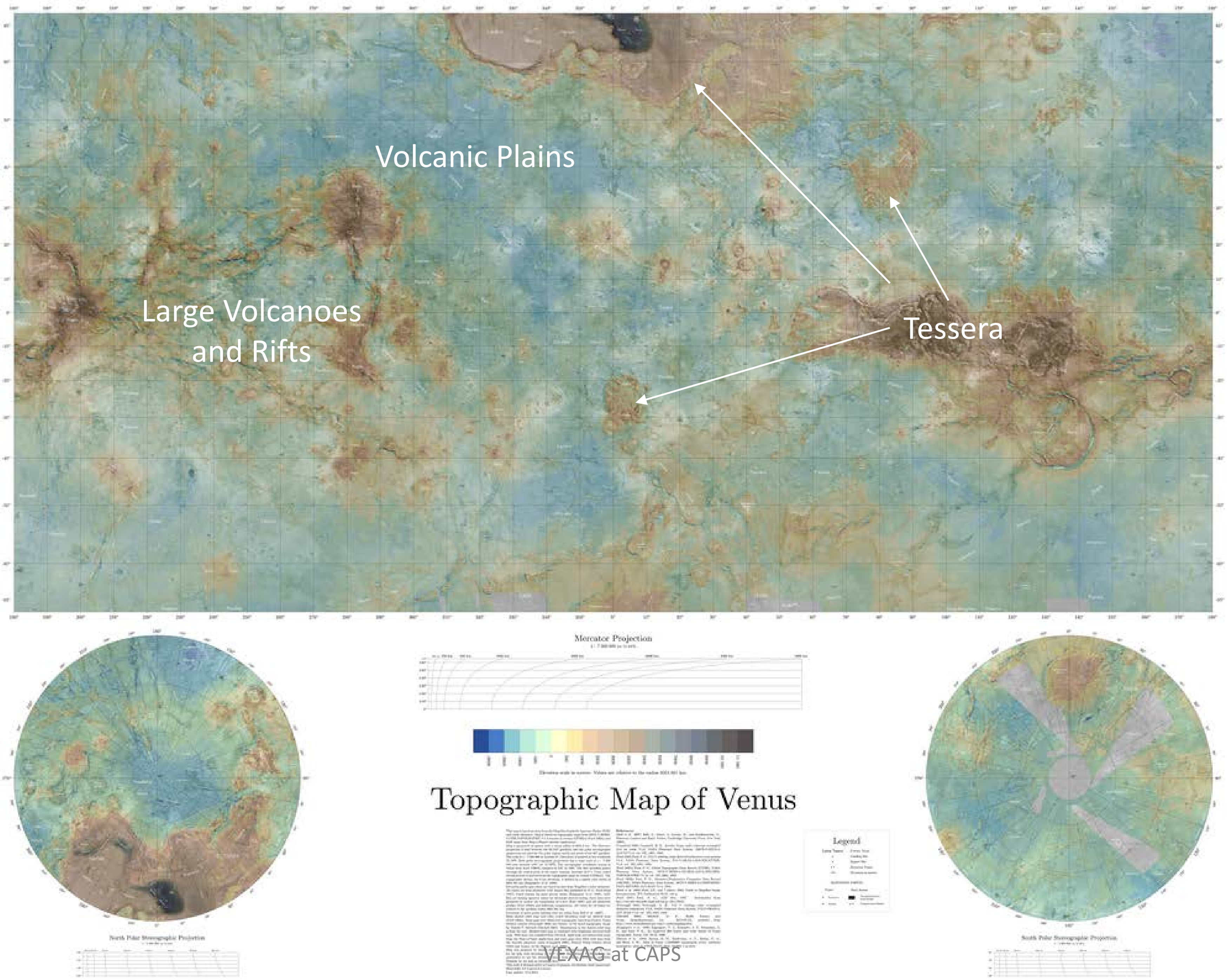
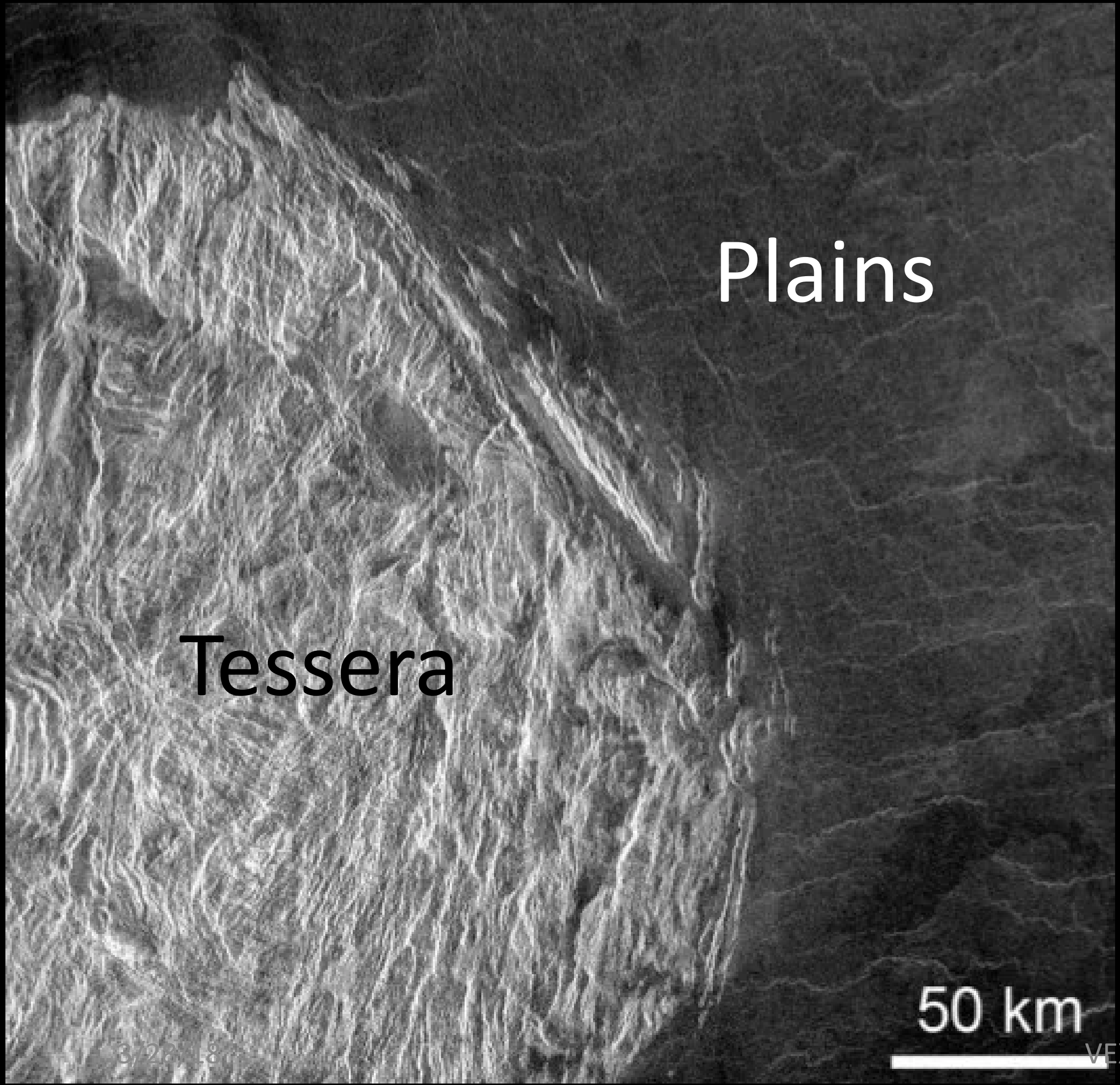


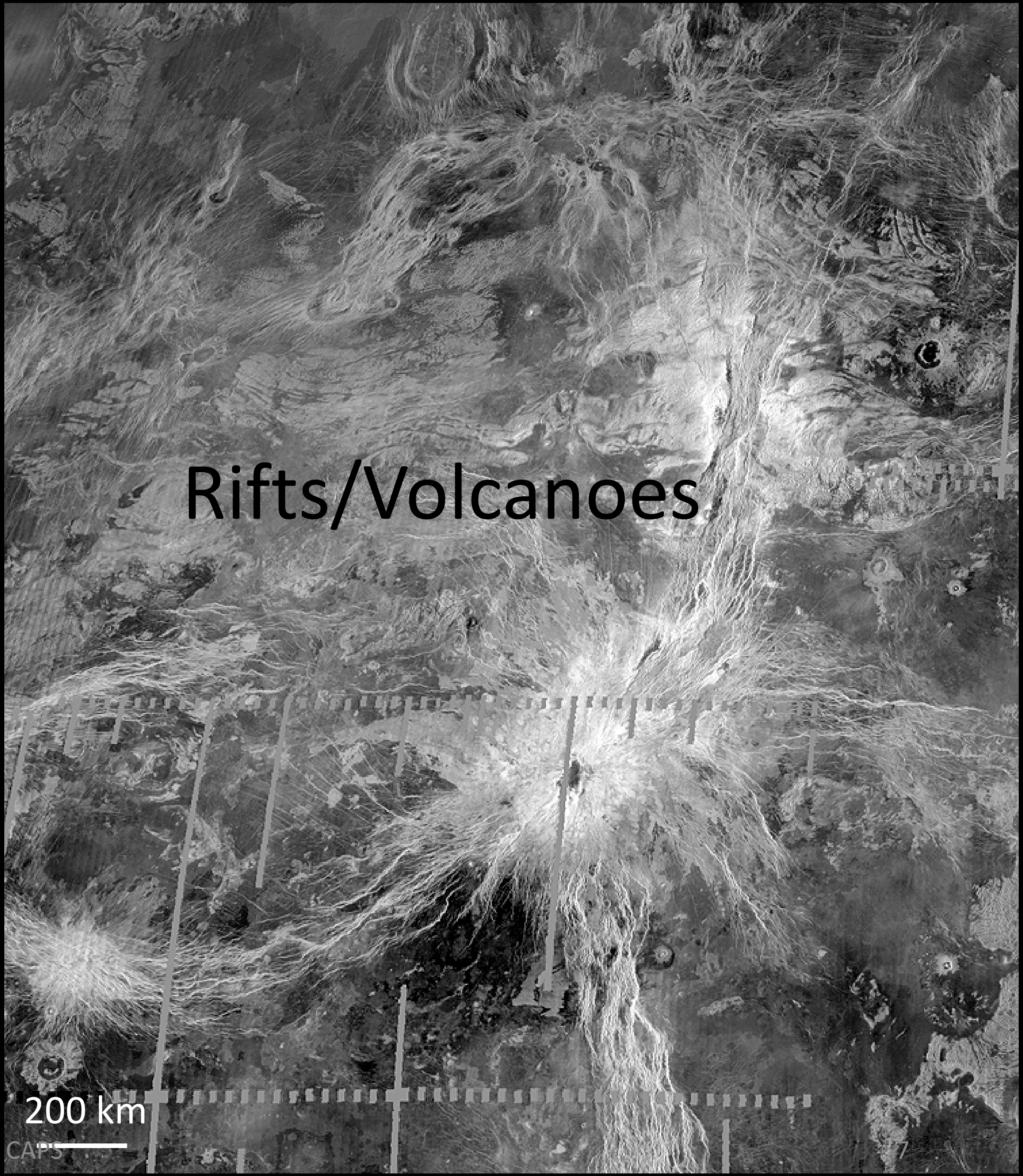
JAXA / ISAS / DARTS / Damia Bouic



Volcanic Plains
Large Volcanoes and Rifts
Tessera
Mercator Projection
Topographic Map of Venus
Legend
North Polar Stereographic Projection
South Polar Stereographic Projection

A General Stratigraphy





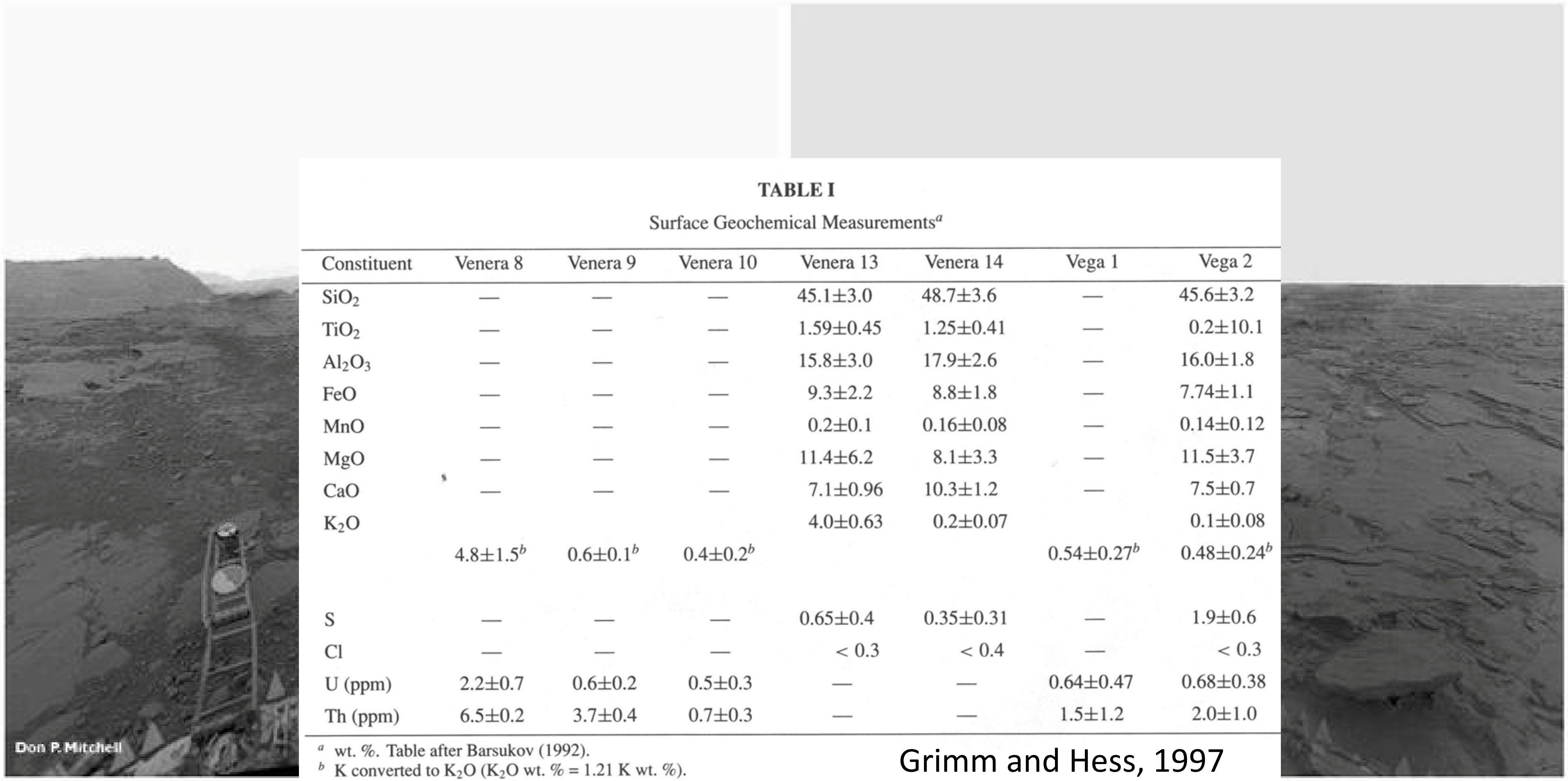


TABLE I

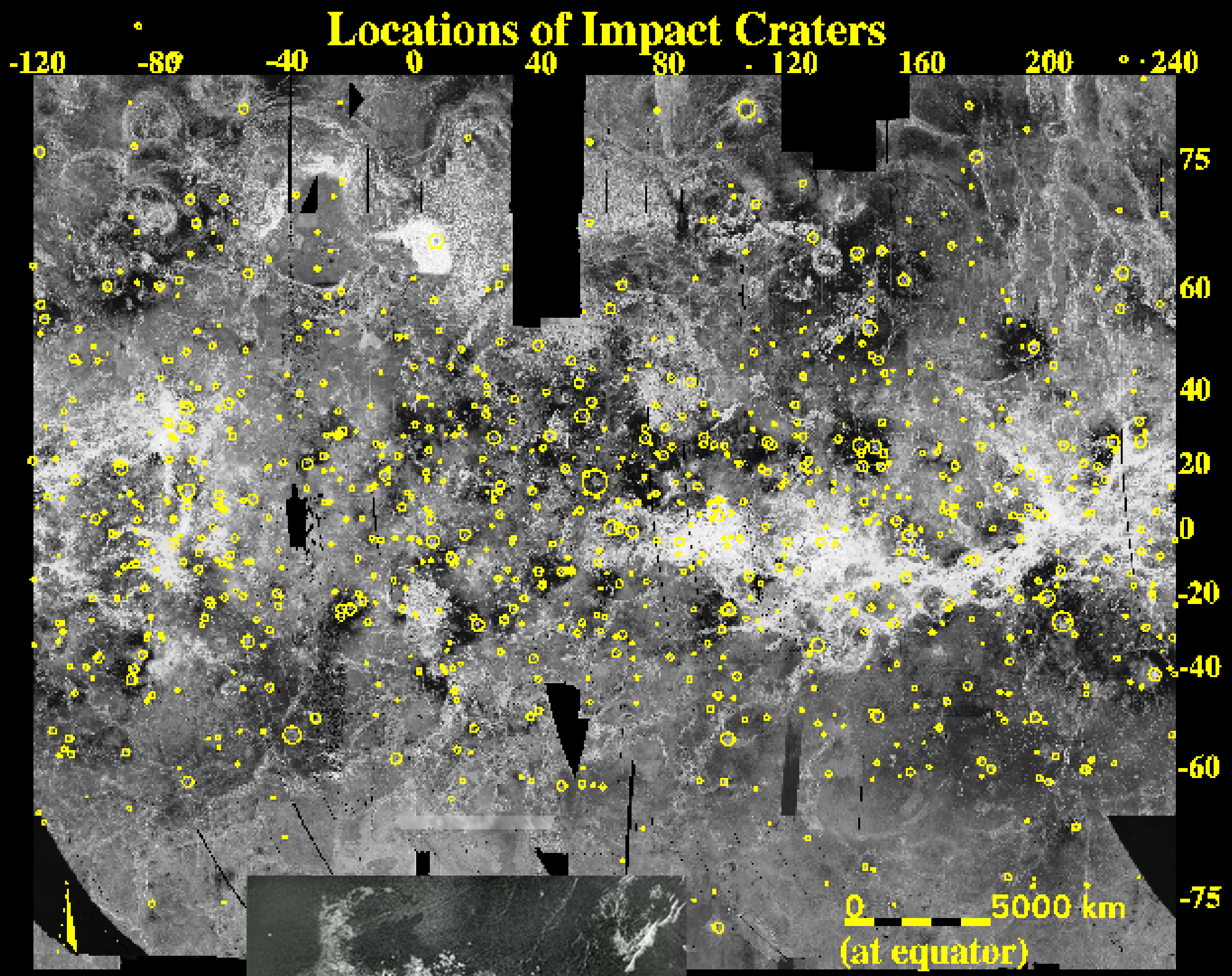
Surface Geochemical Measurements[a]

Constituent	Venera 8	Venera 9	Venera 10	Venera 13	Venera 14	Vega 1	Vega 2
SiO_2	—	—	—	45.1±3.0	48.7±3.6	—	45.6±3.2
TiO_2	—	—	—	1.59±0.45	1.25±0.41	—	0.2±10.1
Al_2O_3	—	—	—	15.8±3.0	17.9±2.6	—	16.0±1.8
FeO	—	—	—	9.3±2.2	8.8±1.8	—	7.74±1.1
MnO	—	—	—	0.2±0.1	0.16±0.08	—	0.14±0.12
MgO	—	—	—	11.4±6.2	8.1±3.3	—	11.5±3.7
CaO	—	—	—	7.1±0.96	10.3±1.2	—	7.5±0.7
K_2O				4.0±0.63	0.2±0.07		0.1±0.08
	4.8±1.5[b]	0.6±0.1[b]	0.4±0.2[b]			0.54±0.27[b]	0.48±0.24[b]
S	—	—	—	0.65±0.4	0.35±0.31	—	1.9±0.6
Cl	—	—	—	< 0.3	< 0.4	—	< 0.3
U (ppm)	2.2±0.7	0.6±0.2	0.5±0.3	—	—	0.64±0.47	0.68±0.38
Th (ppm)	6.5±0.2	3.7±0.4	0.7±0.3	—	—	1.5±1.2	2.0±1.0

[a] wt. %. Table after Barsukov (1992).
[b] K converted to K_2O (K_2O wt. % = 1.21 K wt. %).

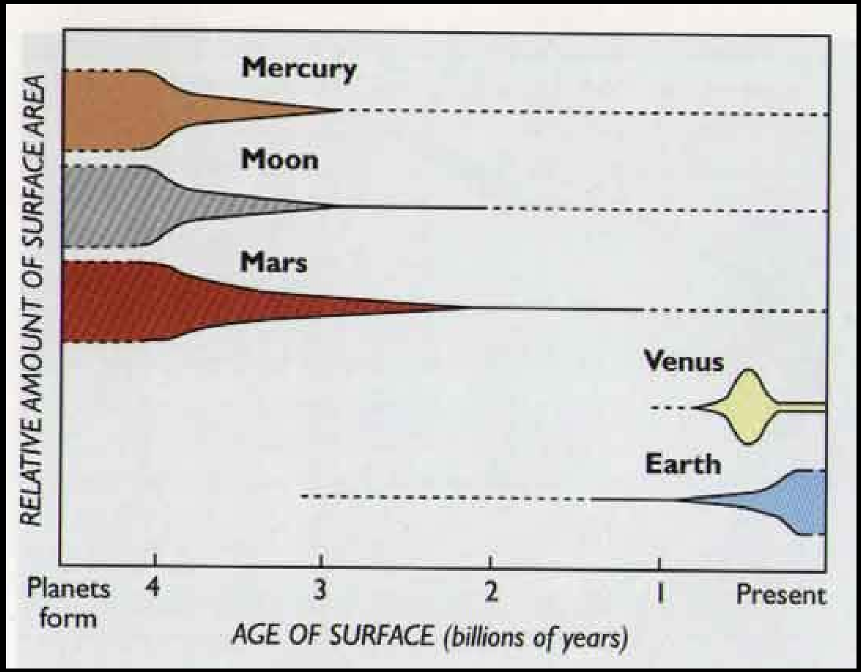
Grimm and Hess, 1997

Venera (1961-1975) landers' gamma ray and/or XRF, measured basalt.



- ~900 craters apparent spatially random, **if** only 4% embayed, consistent with rapid emplacement of surface
- yields average age of ~300 – 1 Ga

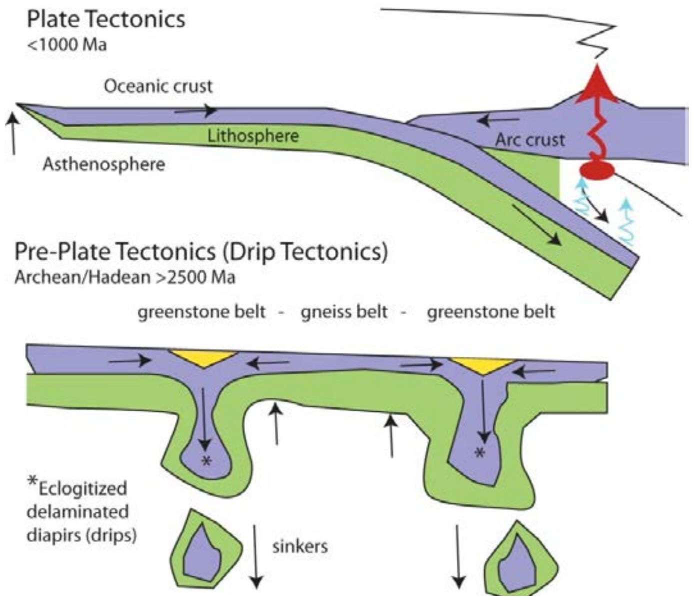
(Phillips et al., 1992; Schaber et al., 1992, McKinnon et al., 1997; Herrick and Rumpf, 2011)

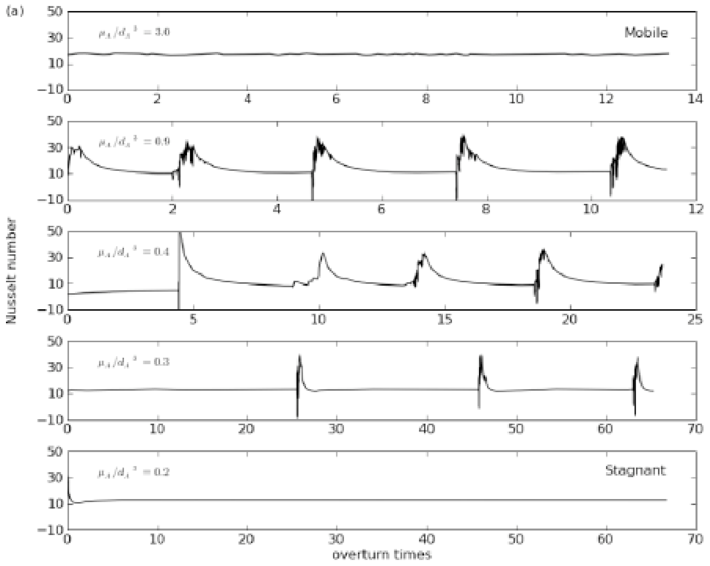


Head et al.

Tectonics: So what will it be?

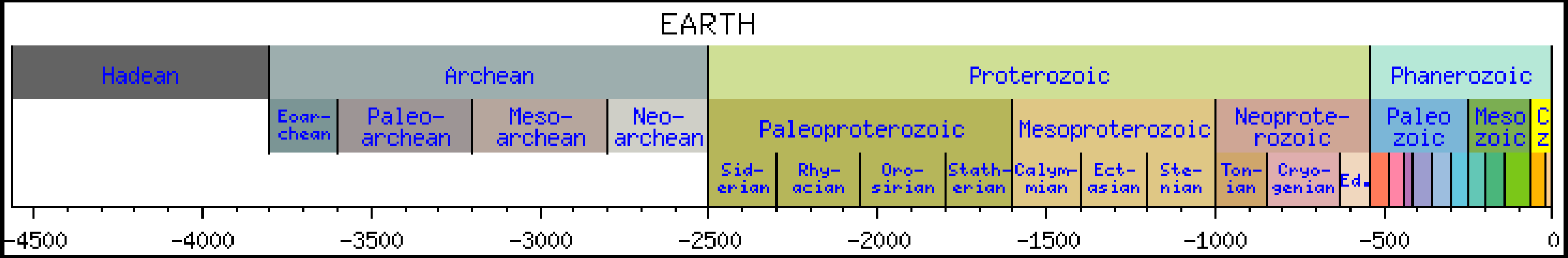
- Stagnant Lid, Mobile Lid, or Something in Between?
- Temperature controls:
  - thickness of lithosphere
  - Strength of convection measured in
    - Ra = $g\alpha\Delta Td^3/\nu\kappa$, or
      - Thermal expansion, thermal diffusivity
    - Nu = heatflux (convection) / heat flux (conduction)= hL/k
      - Convective heat flow, length, thermal conductivity
- Can change with time – ancient Venus, ancient Mars, ancient Earth
- Can vary on a single planet. Technically continents are stagnant lid.
- Water may be an important control on
  - Low viscosity zone
  - Ability of lithosphere to weaken

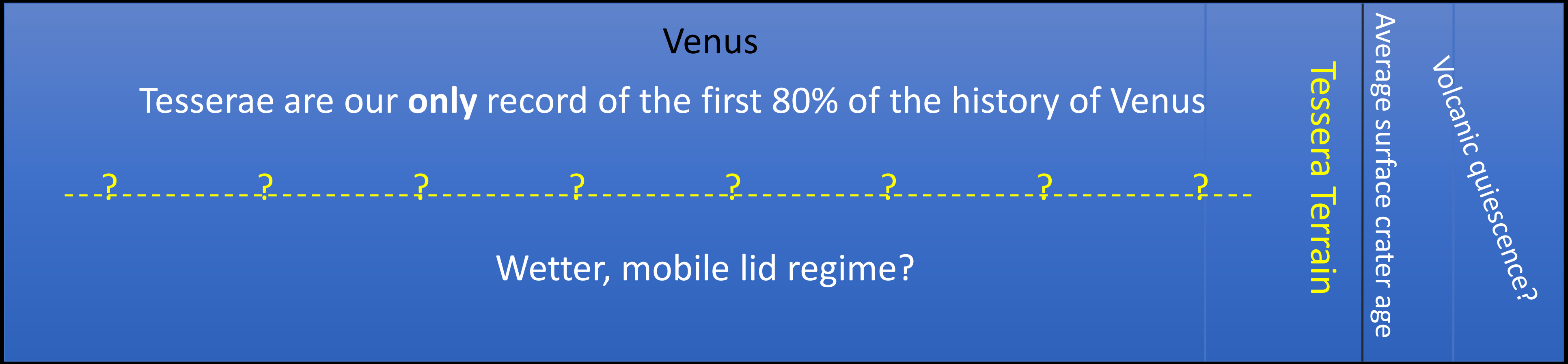




Höink et al.

Venus Stratigraphic Column





Dry? Strong?
basaltic crust
Stagnant Lid
regime

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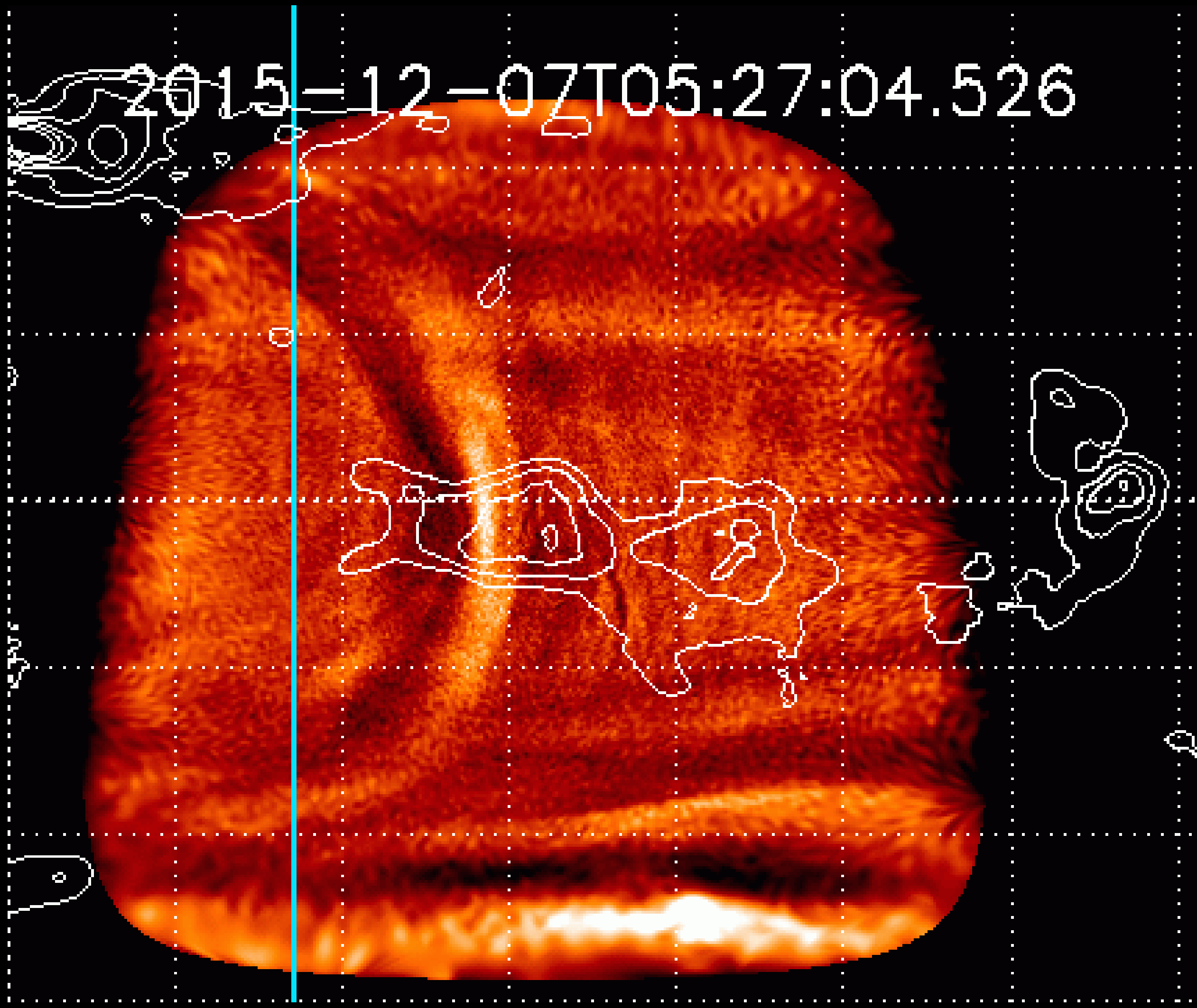
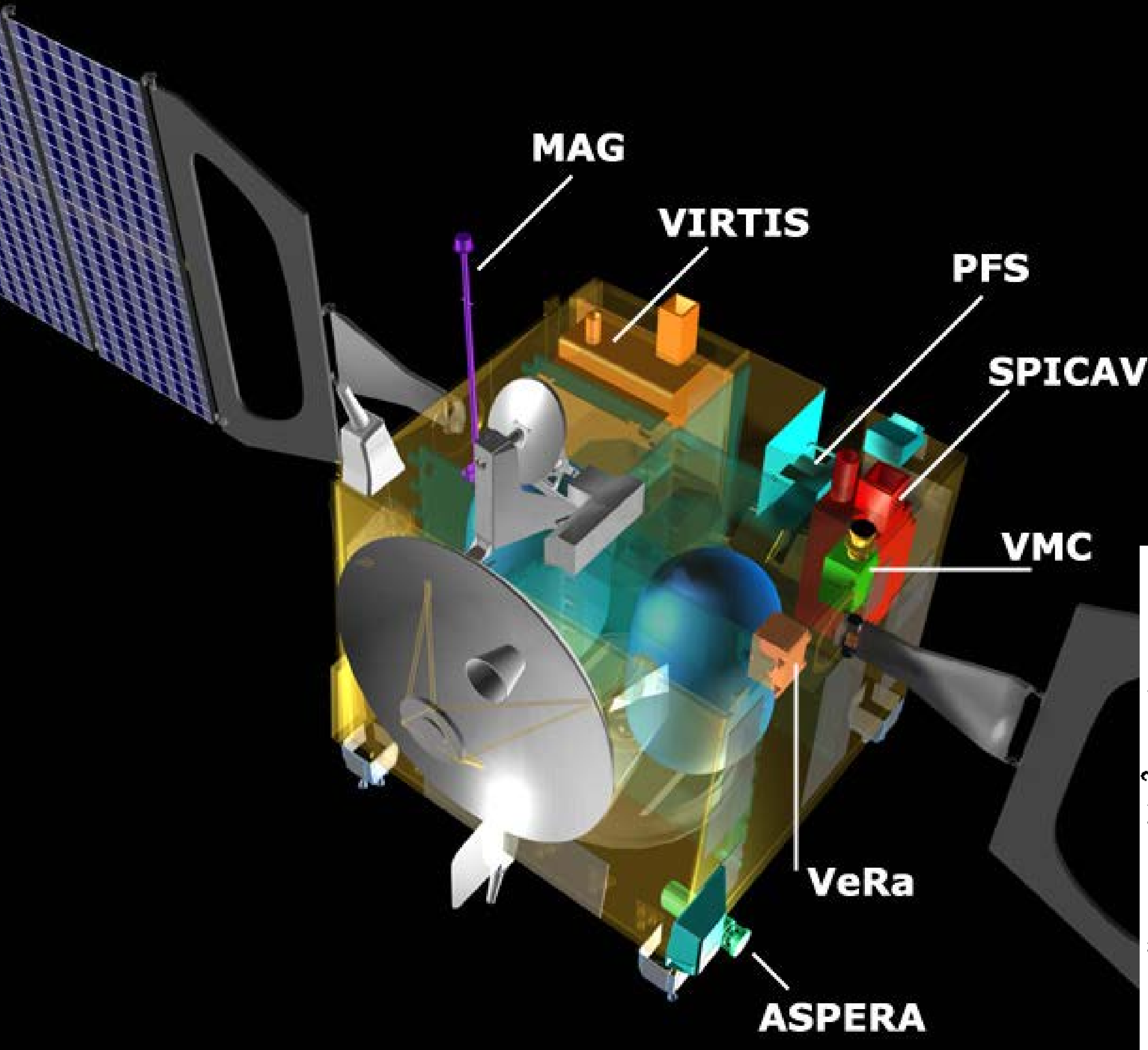
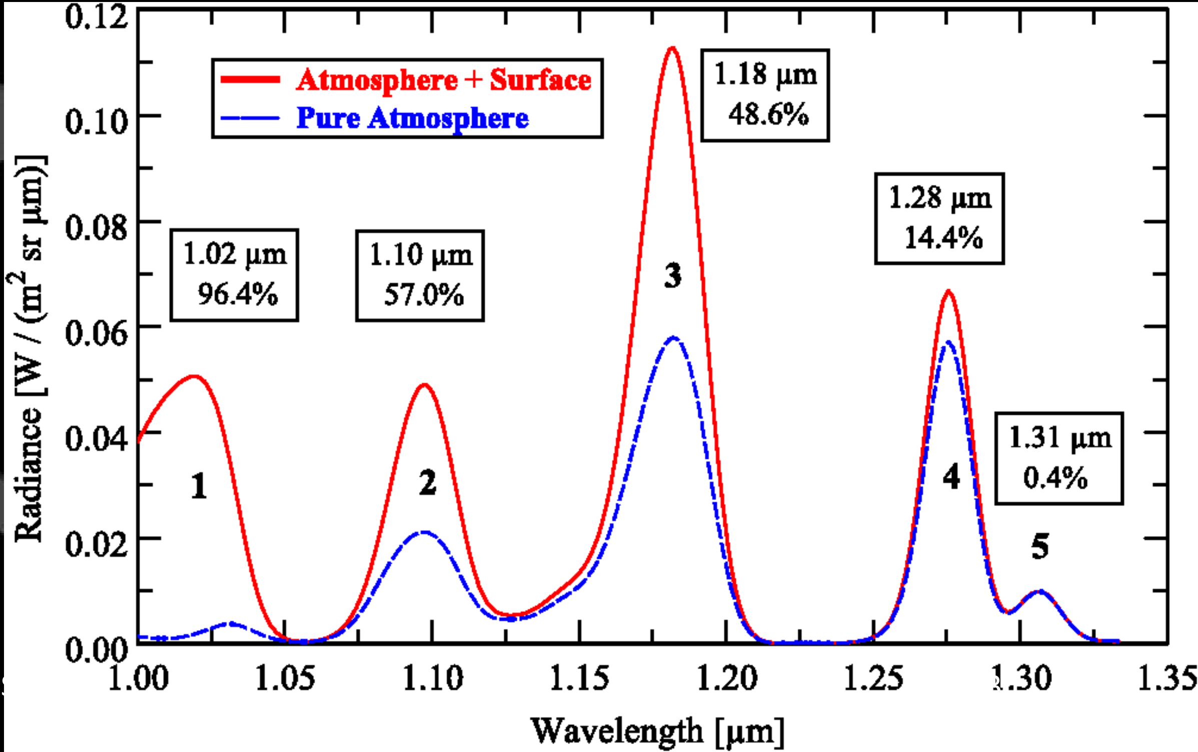


Fukuhara et al 2017

Venus Surface Temperature and Composition ESA Venus Express 2005-2014





Venus at 1 µm

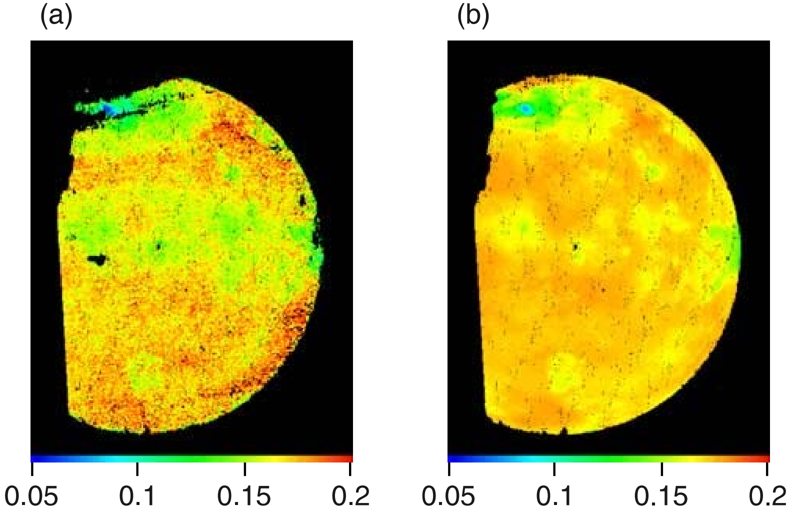
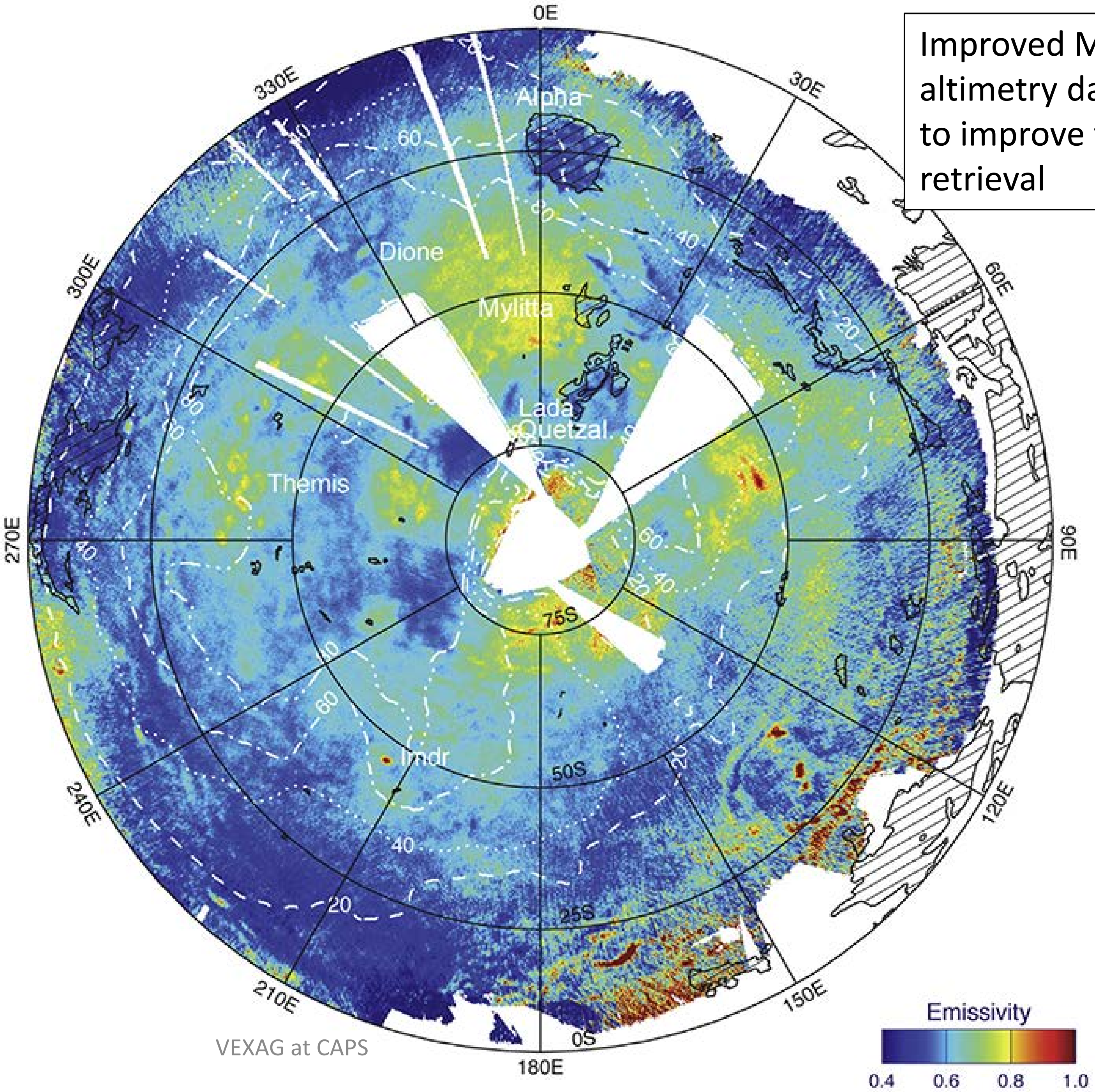


Figure 7. Thermal emission at 1.18 μm window wavelength from the surface and the lower atmosphere. (a) A de-clouded image that is corrected the cloud-induced contrast. (b) A synthesized image based on the Magellan topographic map.

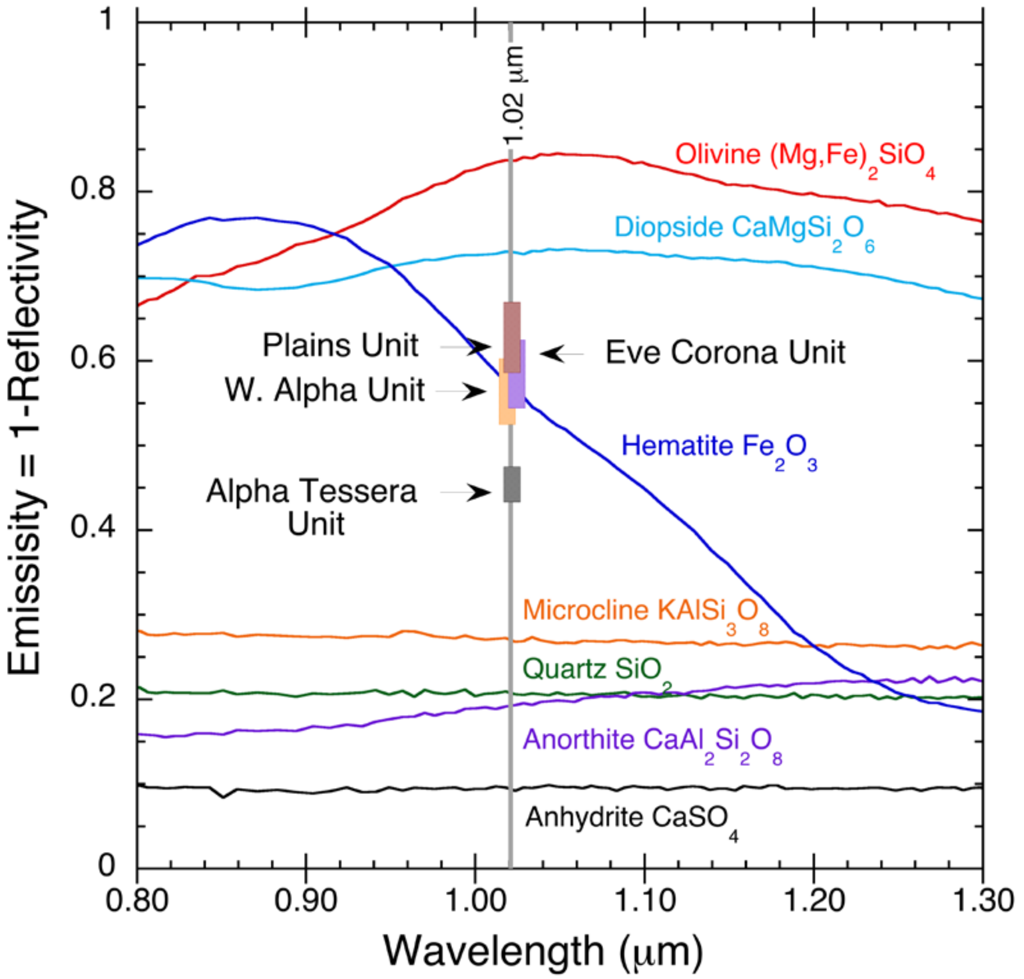
Galileo NIMS
Hashimoto et al. 2008

See also:
Basilevsky et al (2012) VMC data



Improved Magellan altimetry data critical to improve this retrieval

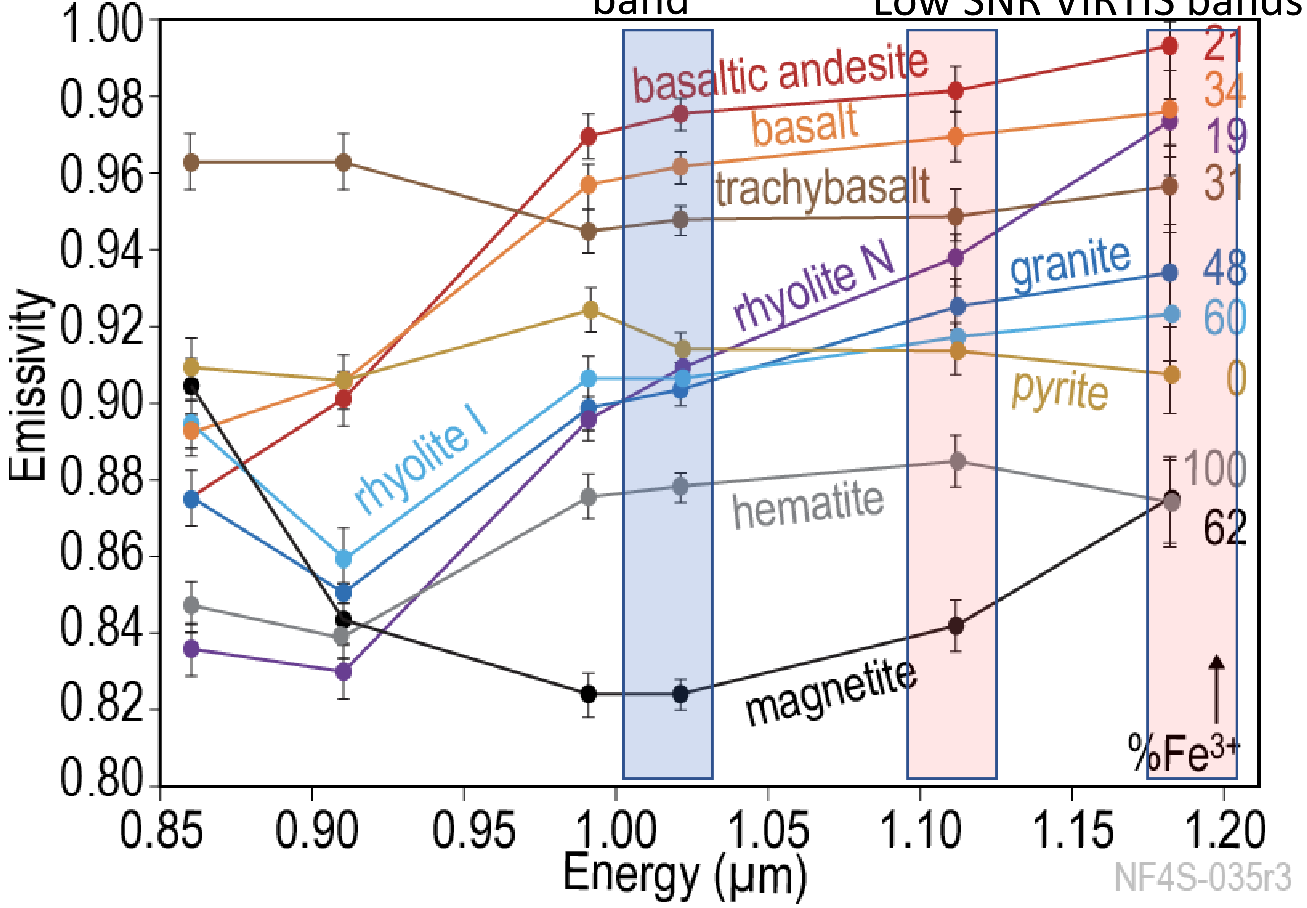
Atmospheric Windows vs. Lab Spectra



Room Temperature

Moderate SNR VIRTIS band

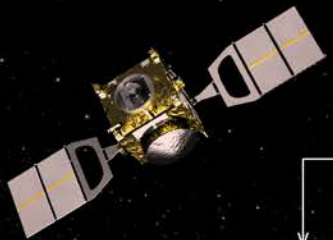
Low SNR VIRTIS bands

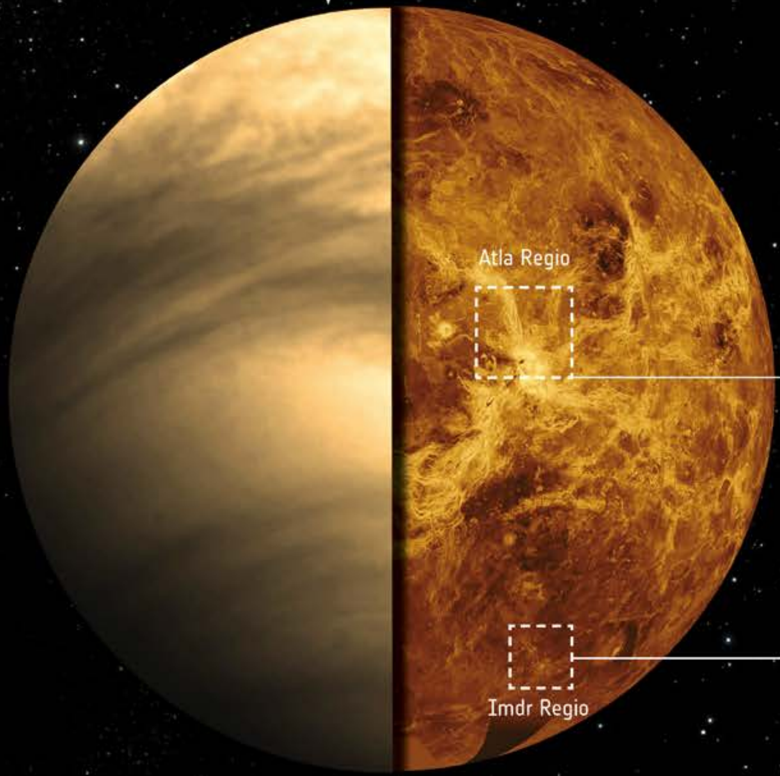


Venus Temperature (DLR lab)

→ EVIDENCE FOR ACTIVE VOLCANOES ON VENUS

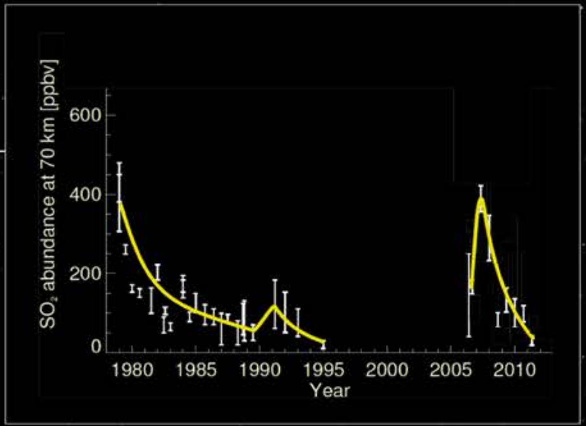
esa





Left: False-colour image of Venus cloud tops (credits: ESA/MPS/DLR/IDA); right: Magellan radar map of Venus (credits: NASA/JPL). The cloud tops image is a local view over high southern latitudes whereas the radar image is a global view centred on the equator.

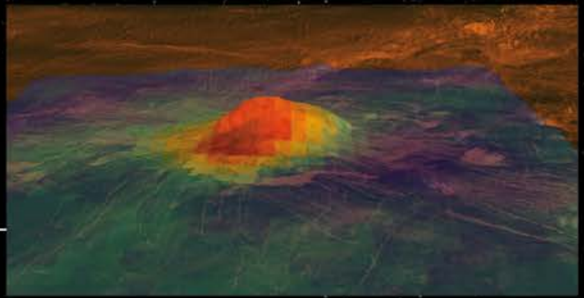
ATMOSPHERIC CHANGES



The rise and fall of sulphur dioxide (SO_2) in the upper atmosphere of Venus over the last 40 years, seen by NASA's Pioneer Venus and other spacecraft between 1978 and 1995, and ESA's Venus Express between 2006 and 2012. A possible explanation is the injection of SO_2 into the atmosphere by volcanic eruptions.

Credits: E. Marcq et al (2012)

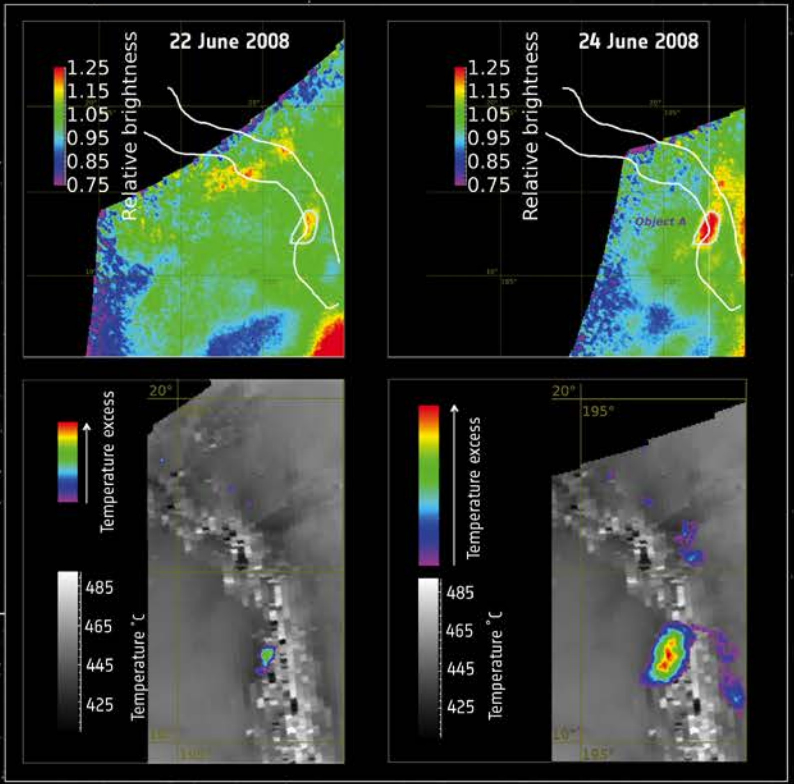
YOUNG LAVA



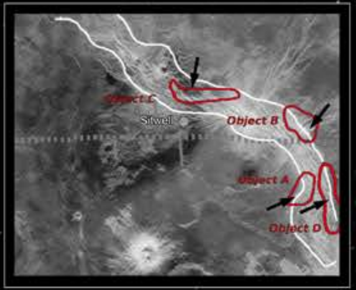
Venus Express found that the area around Idunn Mons in Imdr Regio was unusually dark compared with its surrounds, suggesting a different, younger, composition, pointing to lava flows within the last 2.5 million years. The map shows near-infrared emissivity; red–orange is high emissivity (darkest), purple is the lowest emissivity.

Credits: ESA/NASA/JPL/S. Smrekar et al (2010)

TRANSIENT HOT SPOTS



Four transient hotspots were detected by Venus Express in the Ganiki Chasma rift zone in Atla Regio (labelled Objects A–D in the radar map, right). Changes in relative brightness (top row) and temperature (bottom row) are shown for Object A. Some changes due to clouds are also visible in the top row. The bottom row shows the temperature excess compared with the average surface background temperature. Taking into account atmospheric effects, hotspot A is likely only 1 square km with a temperature of 830°C.



Credits: E. Shalygin et al (2015)

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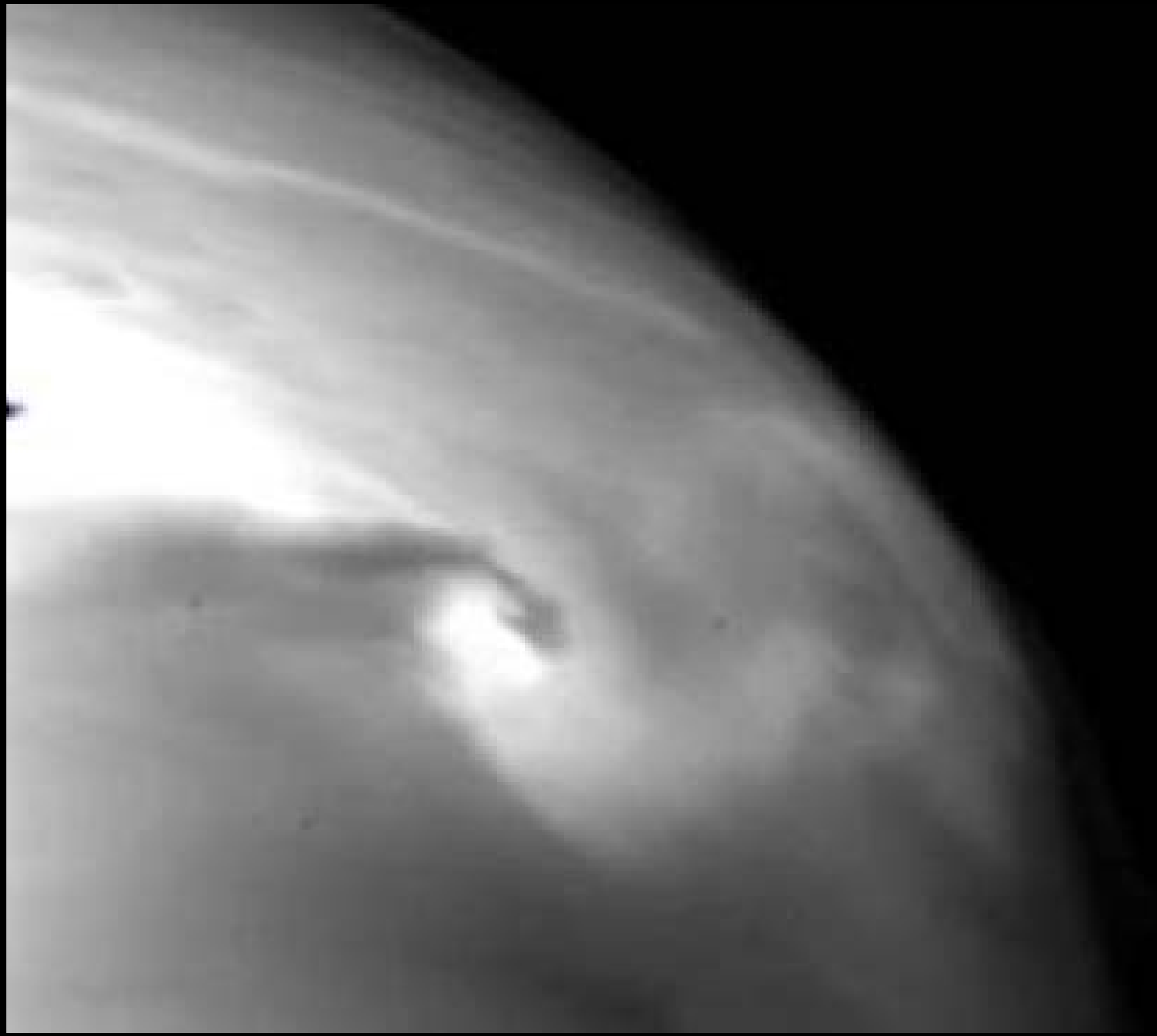
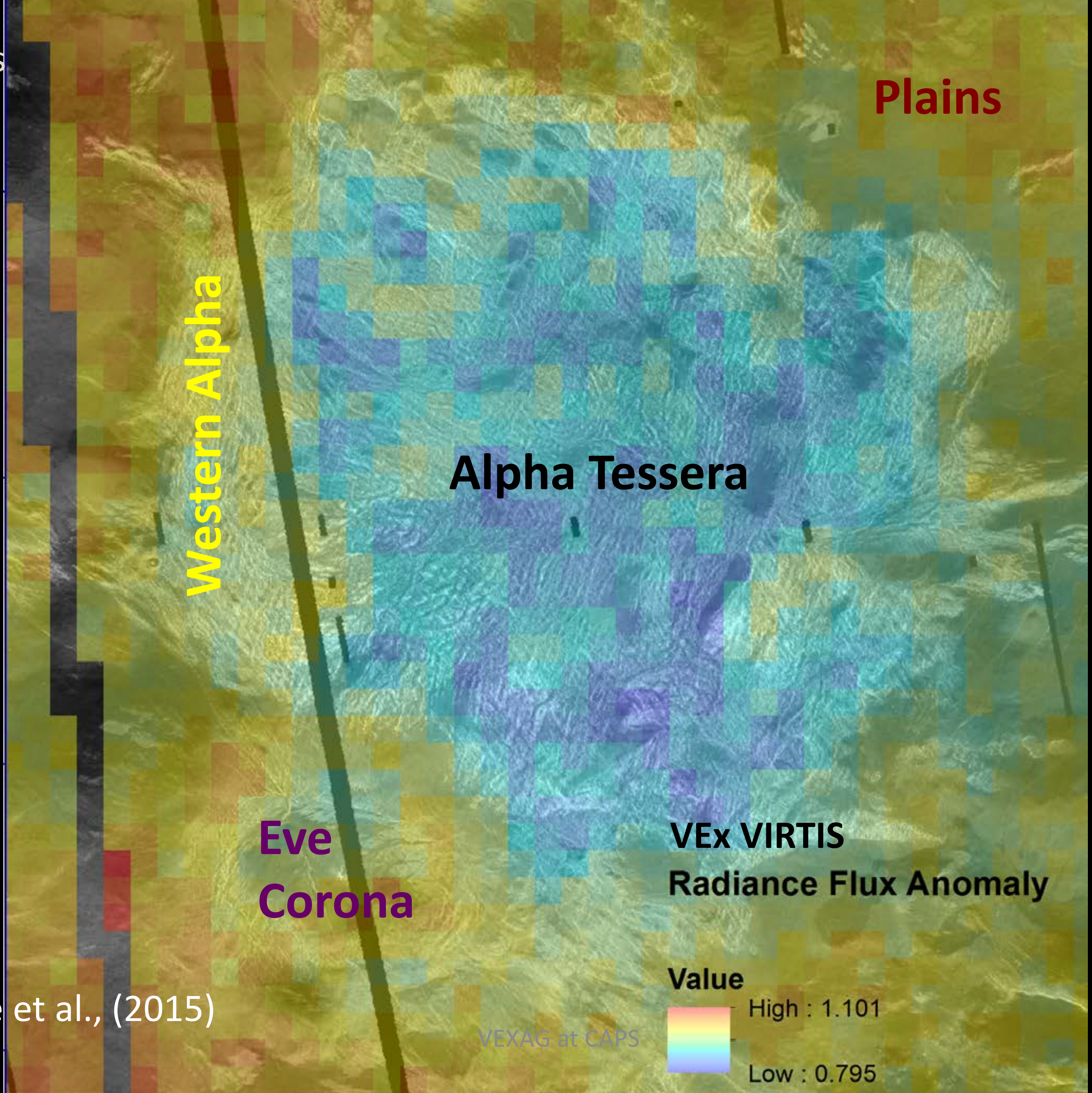
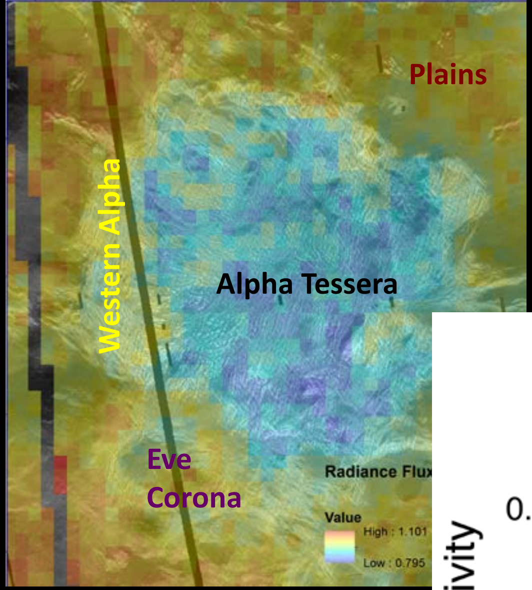


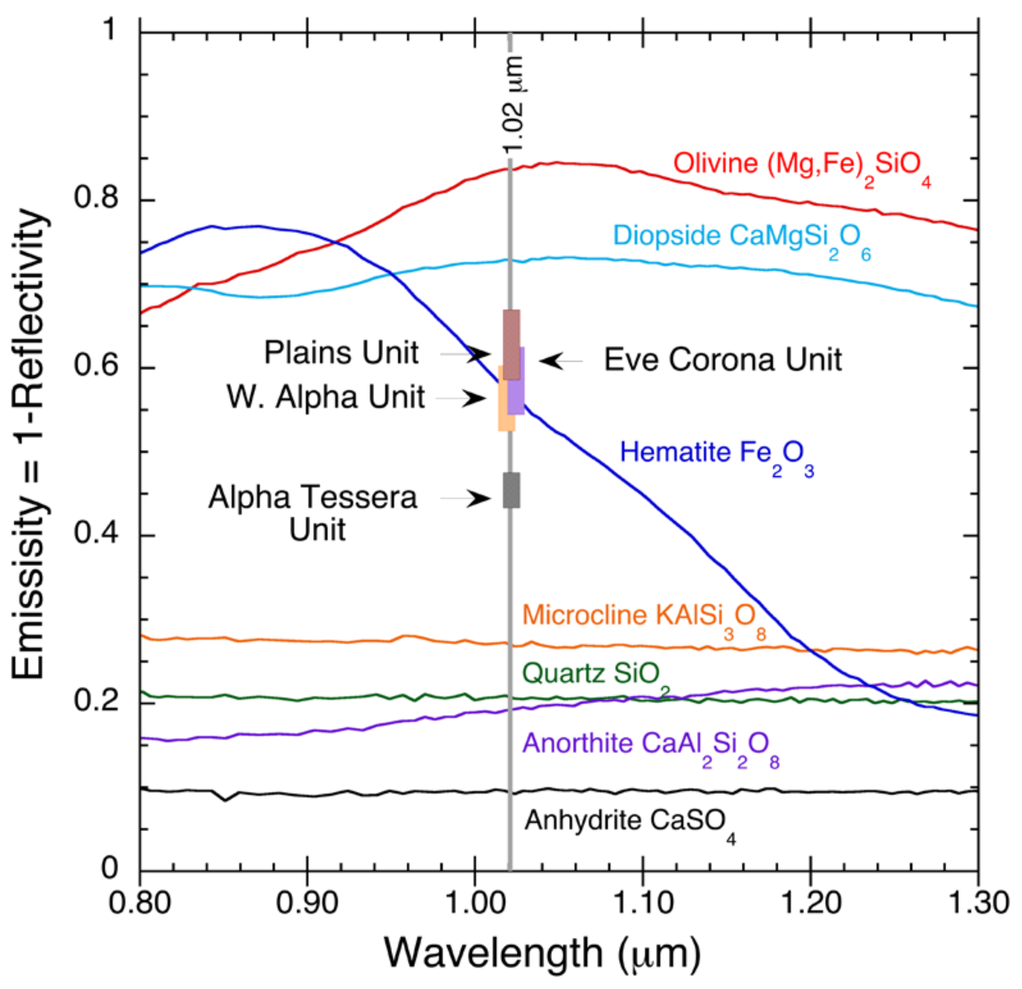
VIRTIS 1 µm Emissivity of Alpha Regio

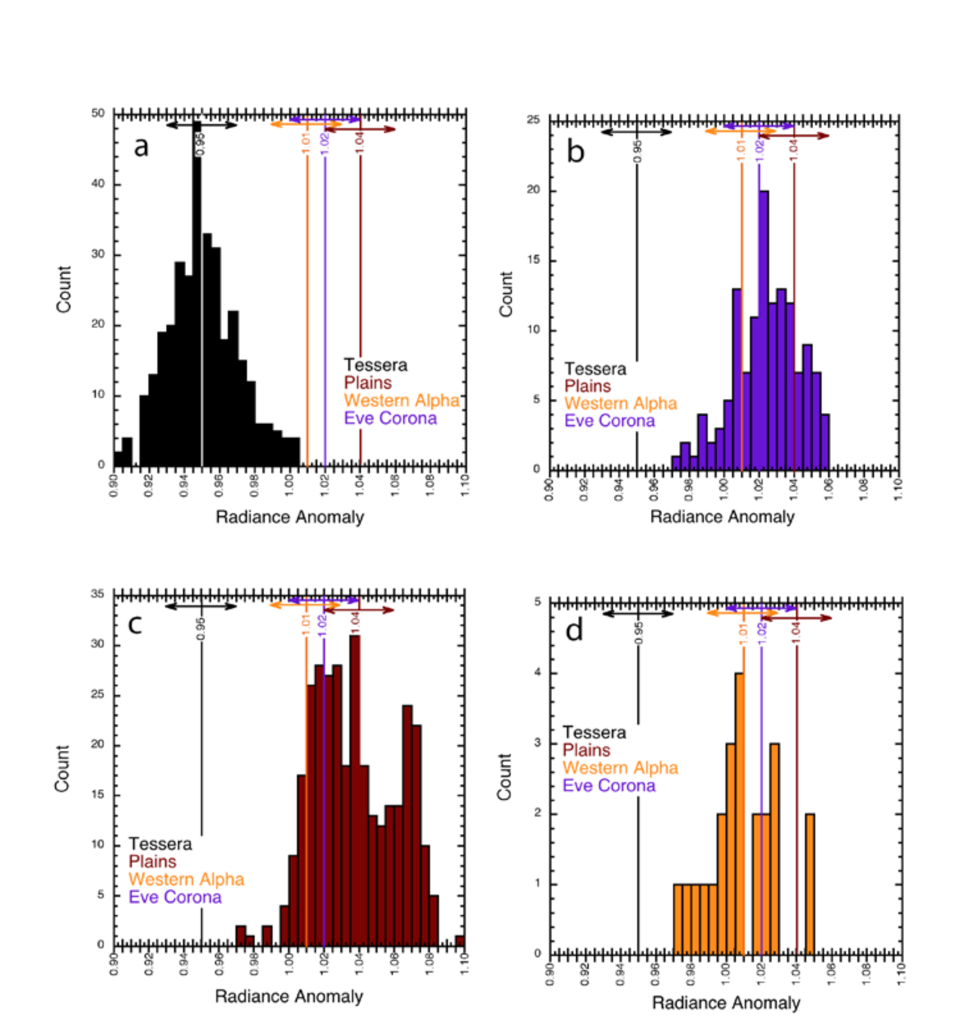
Alpha Regio
W. Alpha is deformed plains
(Gilmore & Head, 2000)
Can control for macroscale
roughness, local effects



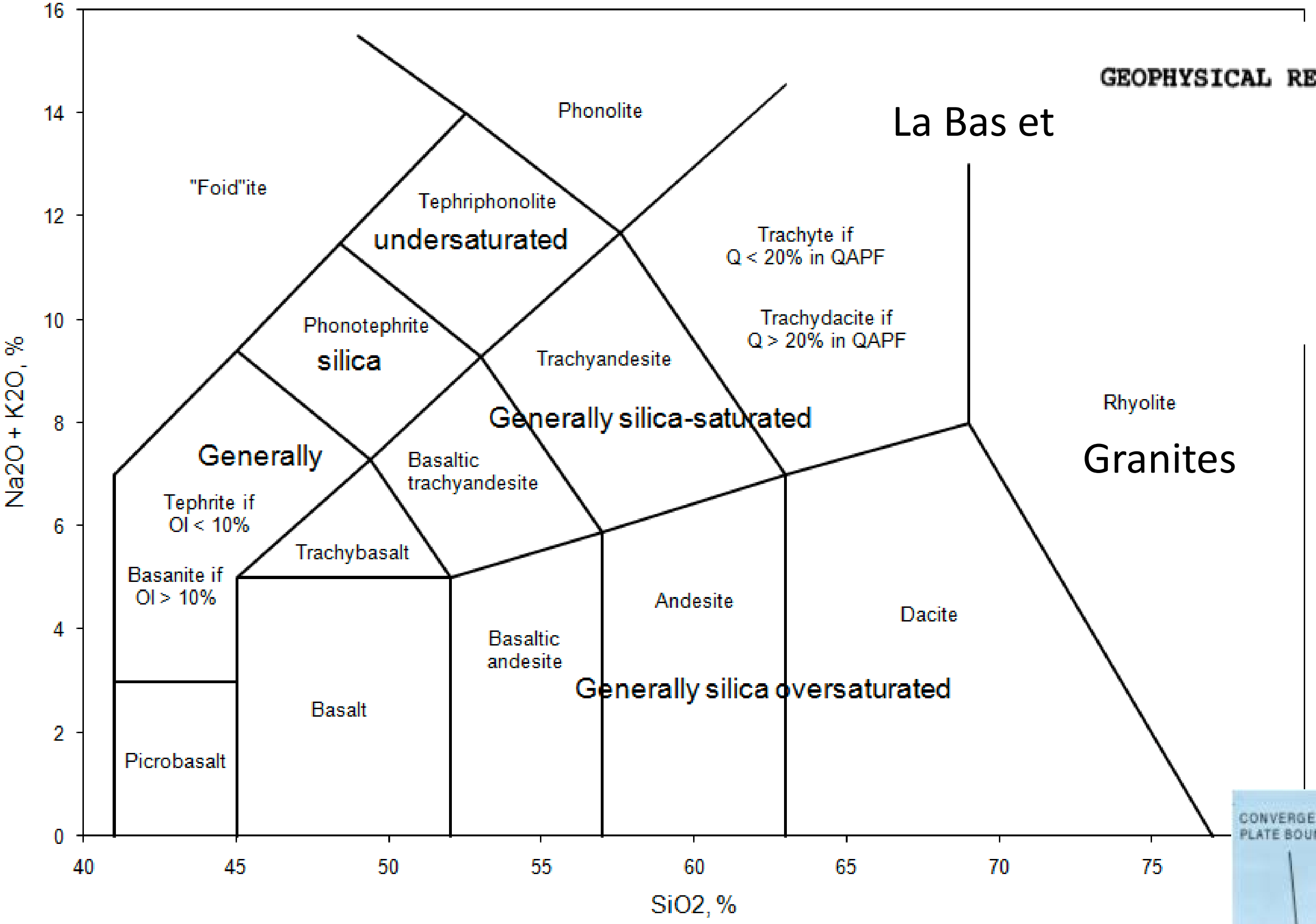
Gilmore et al., (2015)







Gilmore et al. 2015



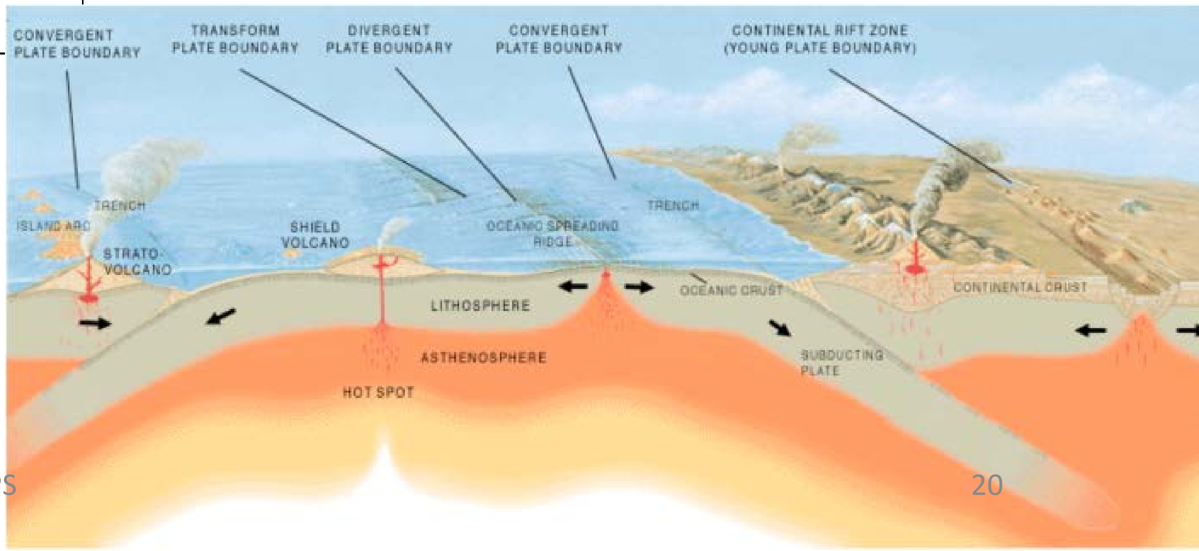
La Bas et

GEOPHYSICAL RESEARCH LETTERS, VOL. 10, NO. 11, PAGES 1061-1064, NOVEMBER 1983

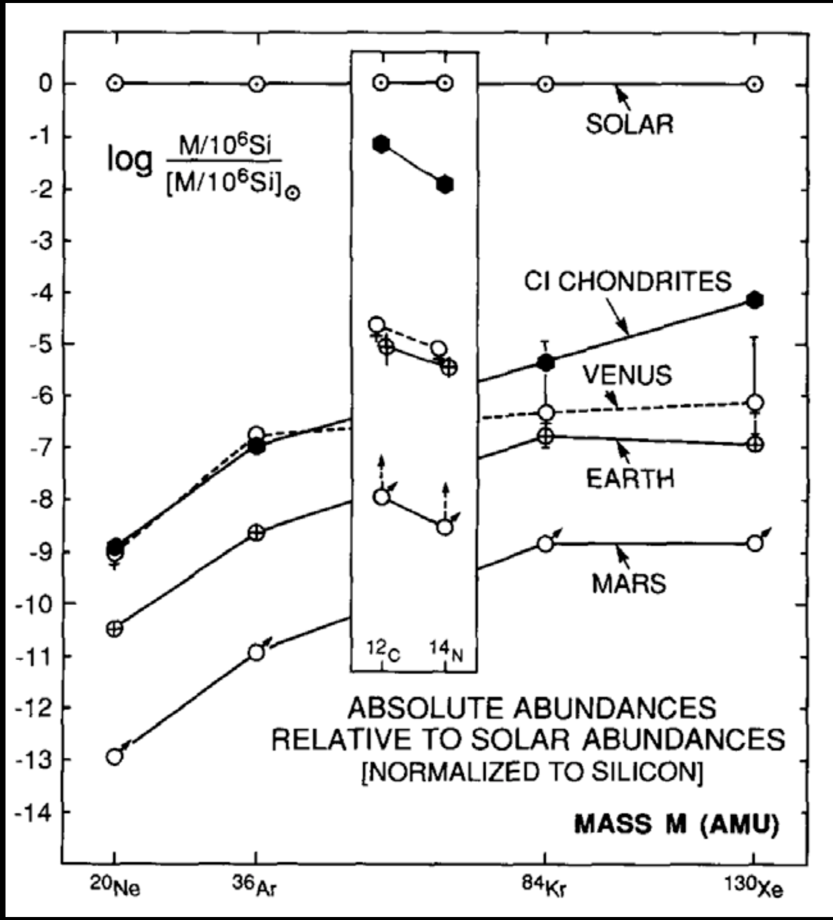
NO WATER, NO GRANITES - NO OCEANS, NO CONTINENTS

I.H. Campbell* and S.R. Taylor

"Our main thesis is simple. Water is essential for the formation of granites, and granite, in turn, is essential for the formation of stable continents. The Earth is the only planet with granite and continents because it is the only planet with abundant water."



Atmospheric Origin and Evolution



- Radiogenic isotopes -> degassing history
- Non radiogenic isotopes -> acquisition and loss
- Stable isotopes HCNO -> origin and evolution of water, accretion scenarios
- The study of Venus also informs the multiple scenarios proposed for Earth and Mars

- In situ measurements required

Pepin 1991

Chassefière et al. 2012

In a global perspective, the only way to reconstruct the detailed history of volatile reservoirs on Venus, from accretion to the end of the heavy bombardment, that is during the first billion years, is to constrain numerical models of the interior-magma ocean–atmosphere–interplanetary space system evolution with present-day noble gas abundances and isotopic fractionation patterns, and with ratios of stable isotopes through the use of the powerful techniques of isotopic geodynamics. If any evidence for past liquid water is found at the surface by future landers, the mineralogical record could be used to better constrain such evolution models.

Early water

Deuterium on Venus: Observations From Earth

CATHERINE DE BERGH, BRUNO BÉZARD, TOBIAS OWEN, DAVID CRISP, JEAN-PIERRE MAILLARD, BARRY L. LUTZ

Absorption lines of HDO and H_2O have been detected in a 0.23–wave number resolution spectrum of the dark side of Venus in the interval 2.34 to 2.43 micrometers, where the atmosphere is sounded in the altitude range from 32 to 42 kilometers (8 to 3 bars). The resulting value of the deuterium-to-hydrogen ratio (D/H) is 120 ± 40 times the telluric ratio, providing unequivocal confirmation of in situ Pioneer Venus mass spectrometer measurements that were in apparent conflict with an upper limit set from International Ultraviolet Explorer spectra. The 100-fold enrichment of the D/H ratio on Venus compared to Earth is thus a fundamental constraint on models for its atmospheric evolution.

1991, *Science*

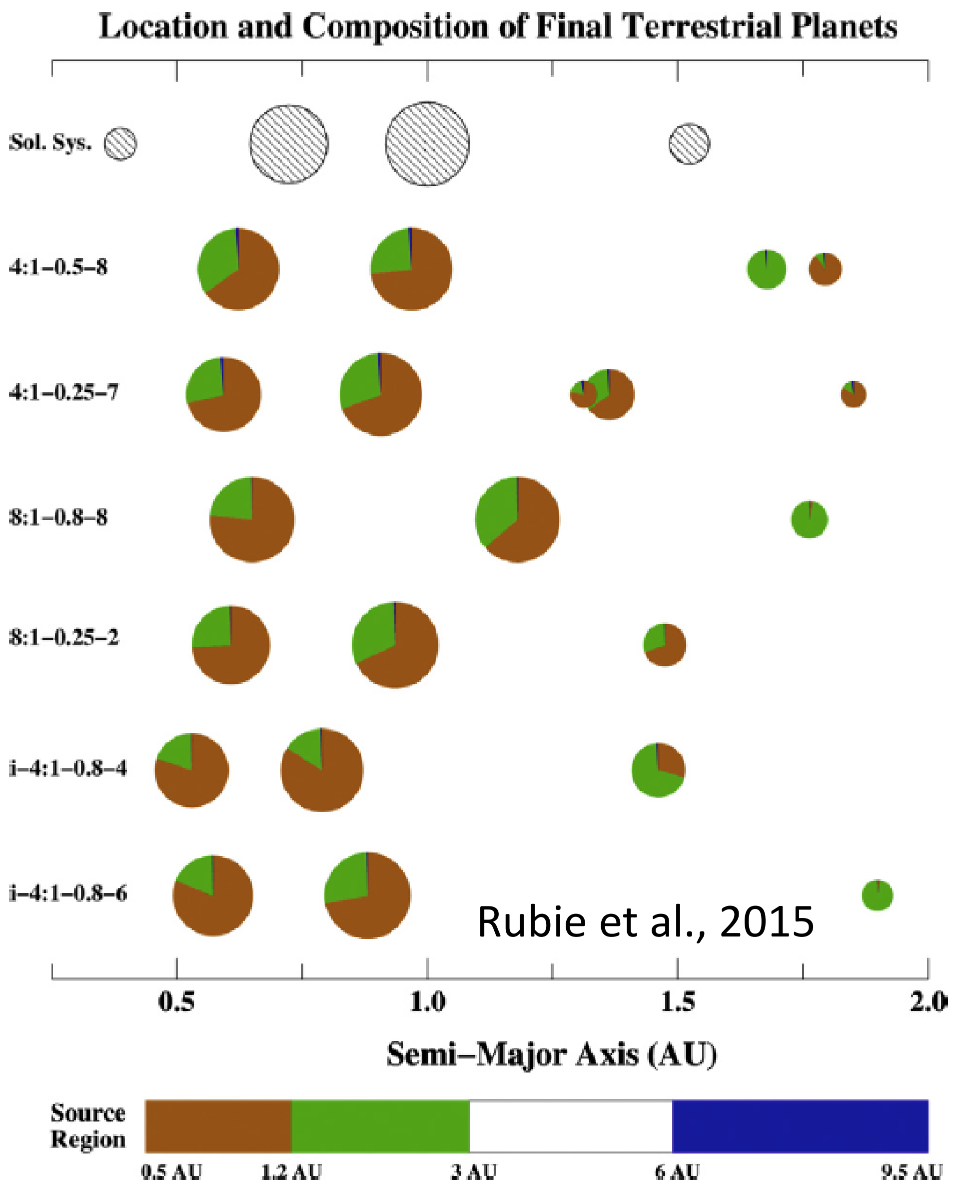
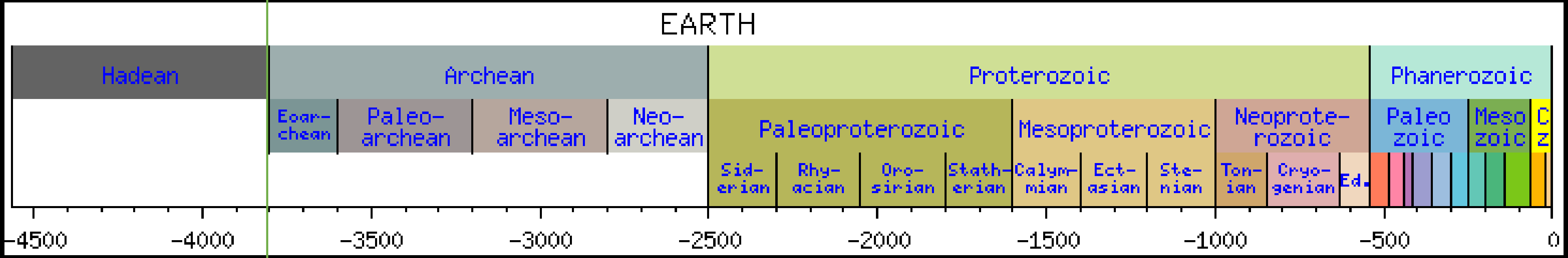
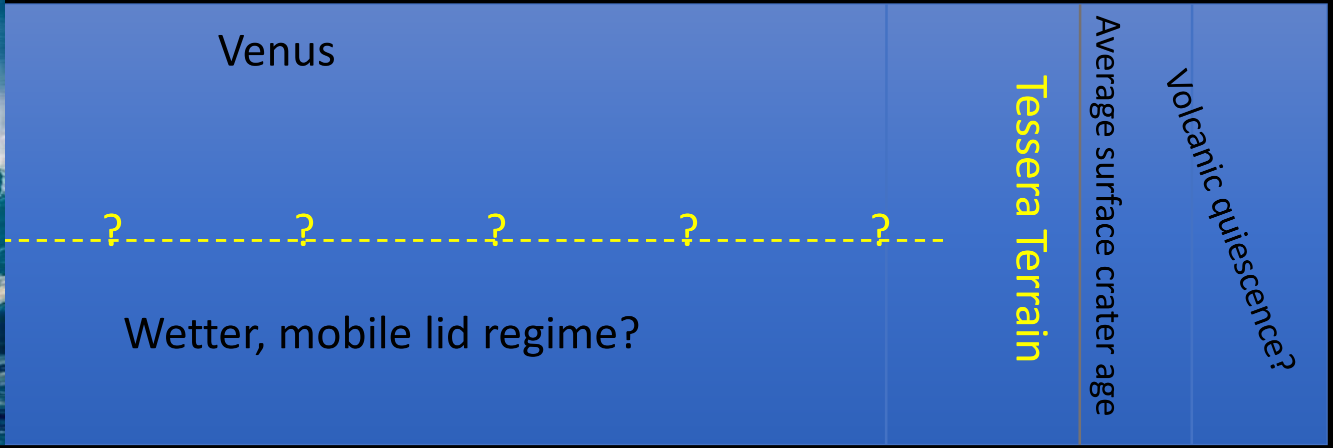


Fig. 1. Mass and location of the final planets in the six Grand Tack simulations of this study. The actual planets of the Solar System are shown at the top for comparison. The colored segments show the proportions of accreted material that originates from 0.5 to 1.2 AU (brown), 1.2 to 3 AU (green) and 6 to 9.5 AU (blue), respectively. Note that no material originates between 3 and 6 AU because the formation of Jupiter and Saturn cleared all bodies from this region. (For interpre-

Venus Stratigraphic Column





3.8 Ga - Oldest evidence of life on Earth (Mojzsis et al., 1996)

D/H Venus atmosphere = 150X terrestrial

Assuming Earth and Venus started with the same inventory…

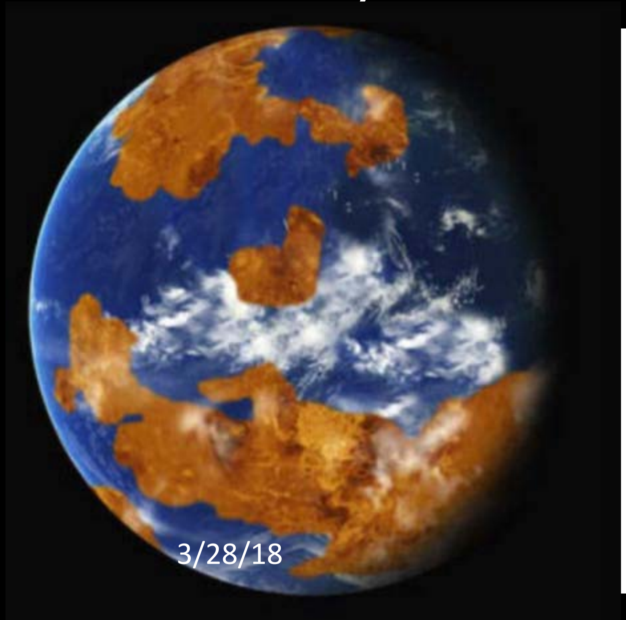
~0.6 – 16% Earth ocean's worth of water (Donahue et al., 1997)

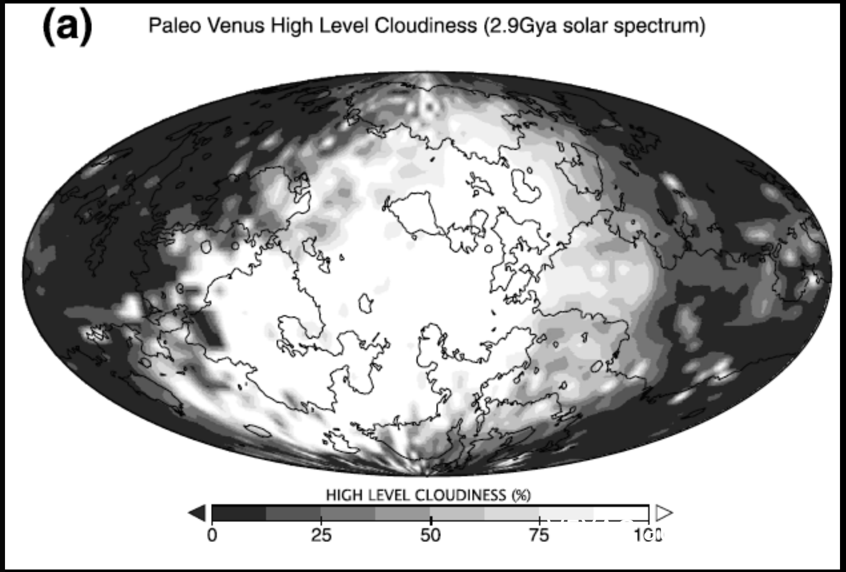
Ocean may have persisted….. For a billion years? (Kasting & Pollack, 1983)

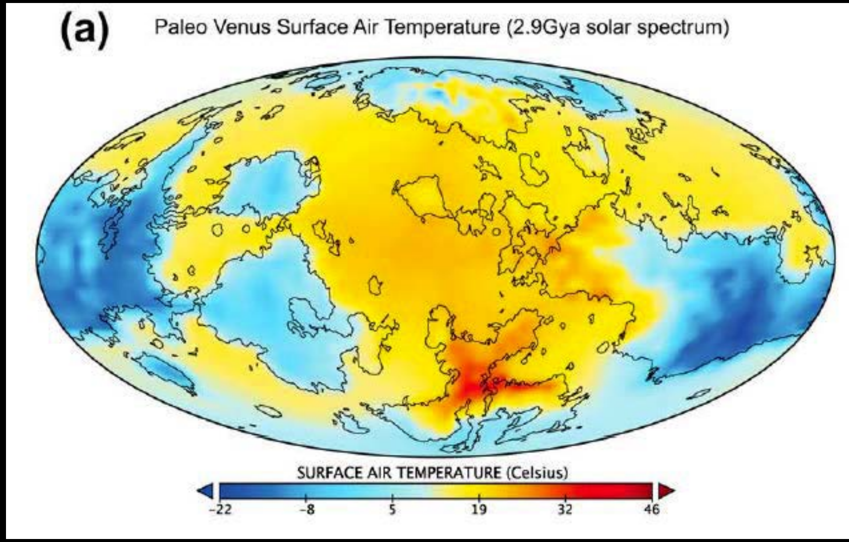
Recent model (Way et al., 2016) predicts ocean for 2-3 Ga.

An Early Ocean Could Persist Until the Recent Past
Way et al., 2016

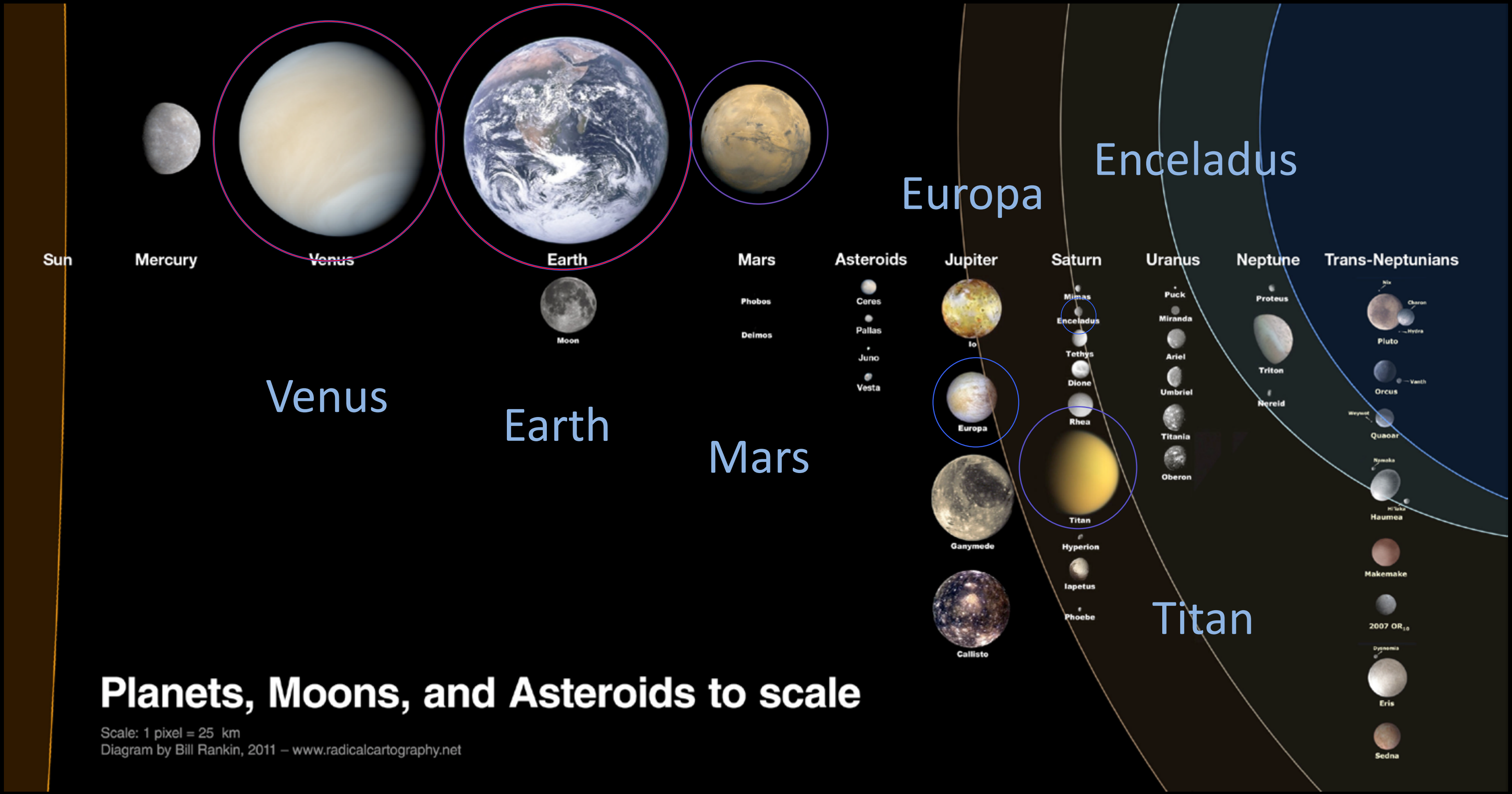
- Slow rotation produces dayside clouds that keep the surface cool and maintain the ocean –positive feedback loop.
- Assumes Earth-like atmosphere, current Venus rotation
- Assumes all elevation<mean is water-filled, yield 310 m ocean
- Insolation at 2.9 and 0.7 Ga tested (yields 11°C vs 15 °C, respectively).
- Some dependence on topography (modern Earth 23°C, modern Venus 15°C)







Habitable Worlds in a Habitable Solar System



Letter

Life in the Clouds of Venus?

HAROLD MOROWITZ & CARL SAGAN

Nature **215**, 1259–1260 (16 September 1967)
doi:10.1038/2151259a0

Received: 04 August 1967
Published: 16 September 1967

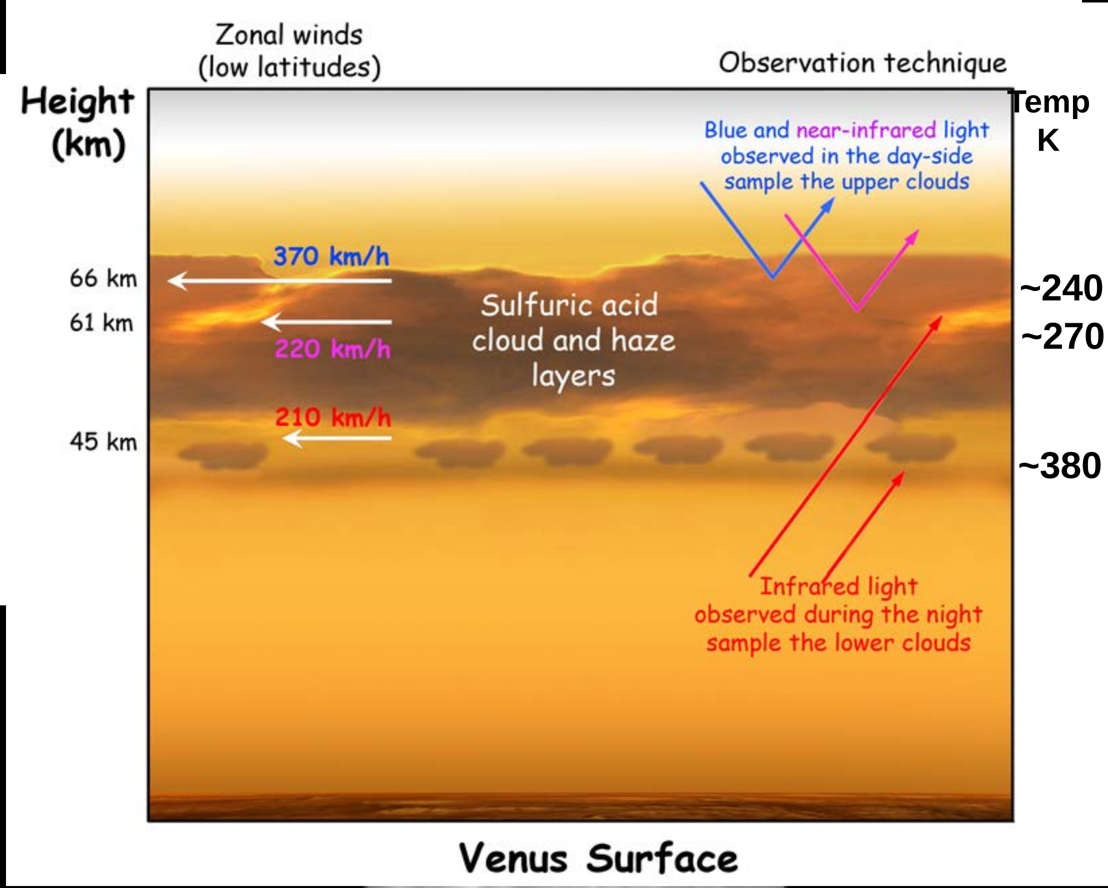
ELSEVIER

Planetary and Space Science

Volume 47, Issue 12, 15 December 1999, Pages 1487-1501

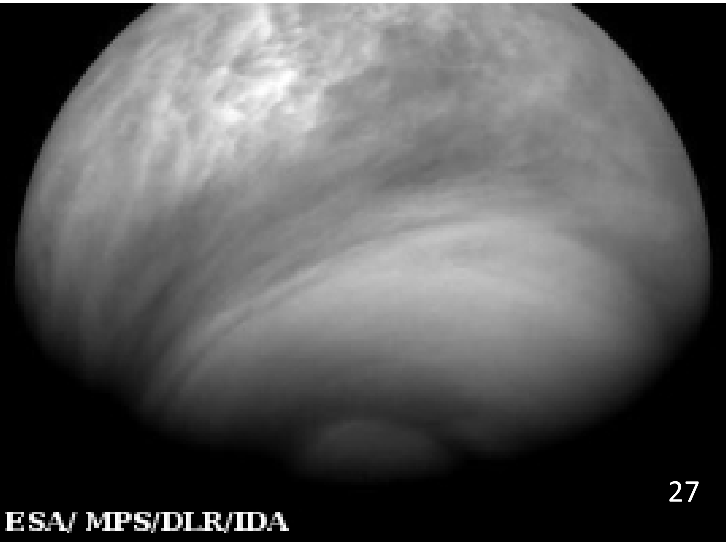
Life on Venus

Charles S Cockell



Limaye et al. forthcoming

OSSO (disulfurdioxide) suggested as ultraviolet absorber *(Frandsenet al, 2016)*



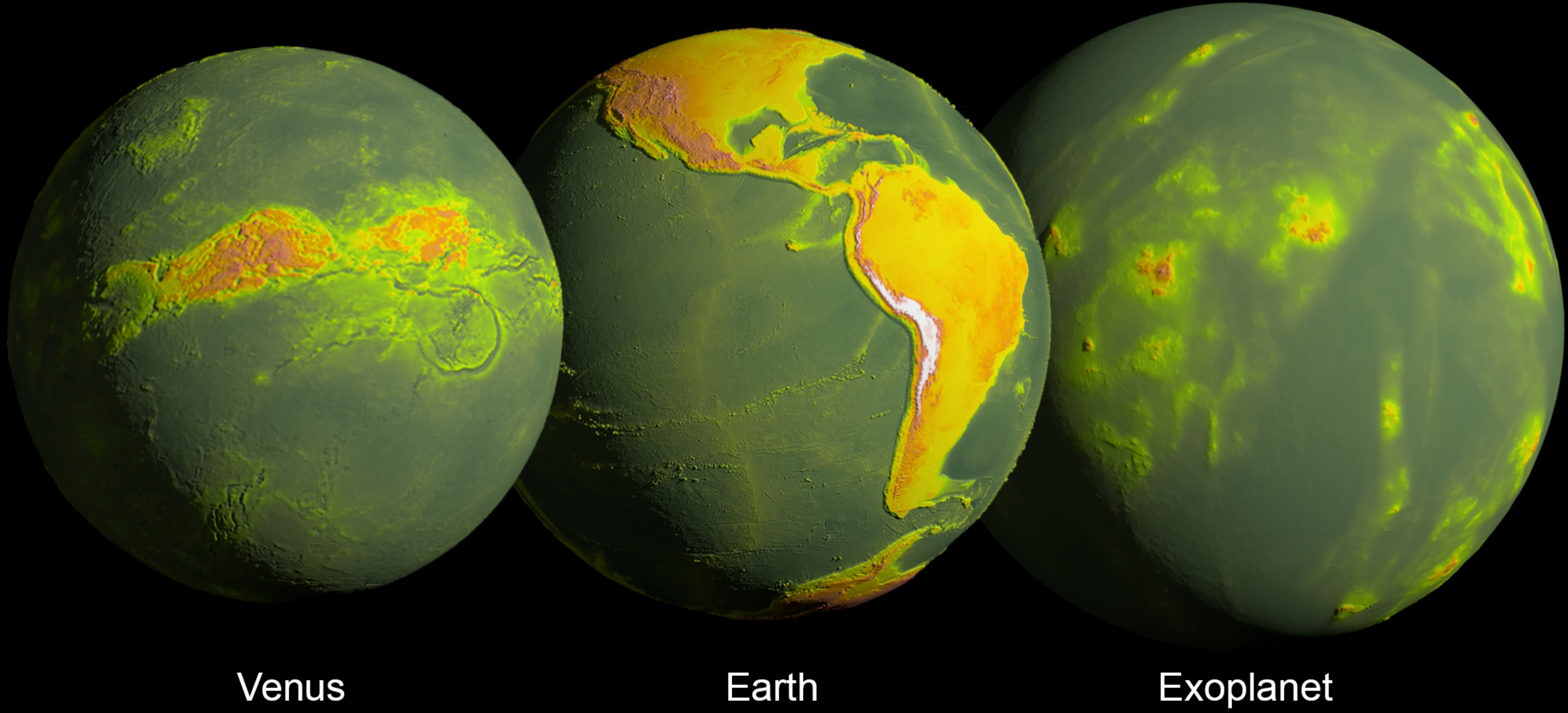
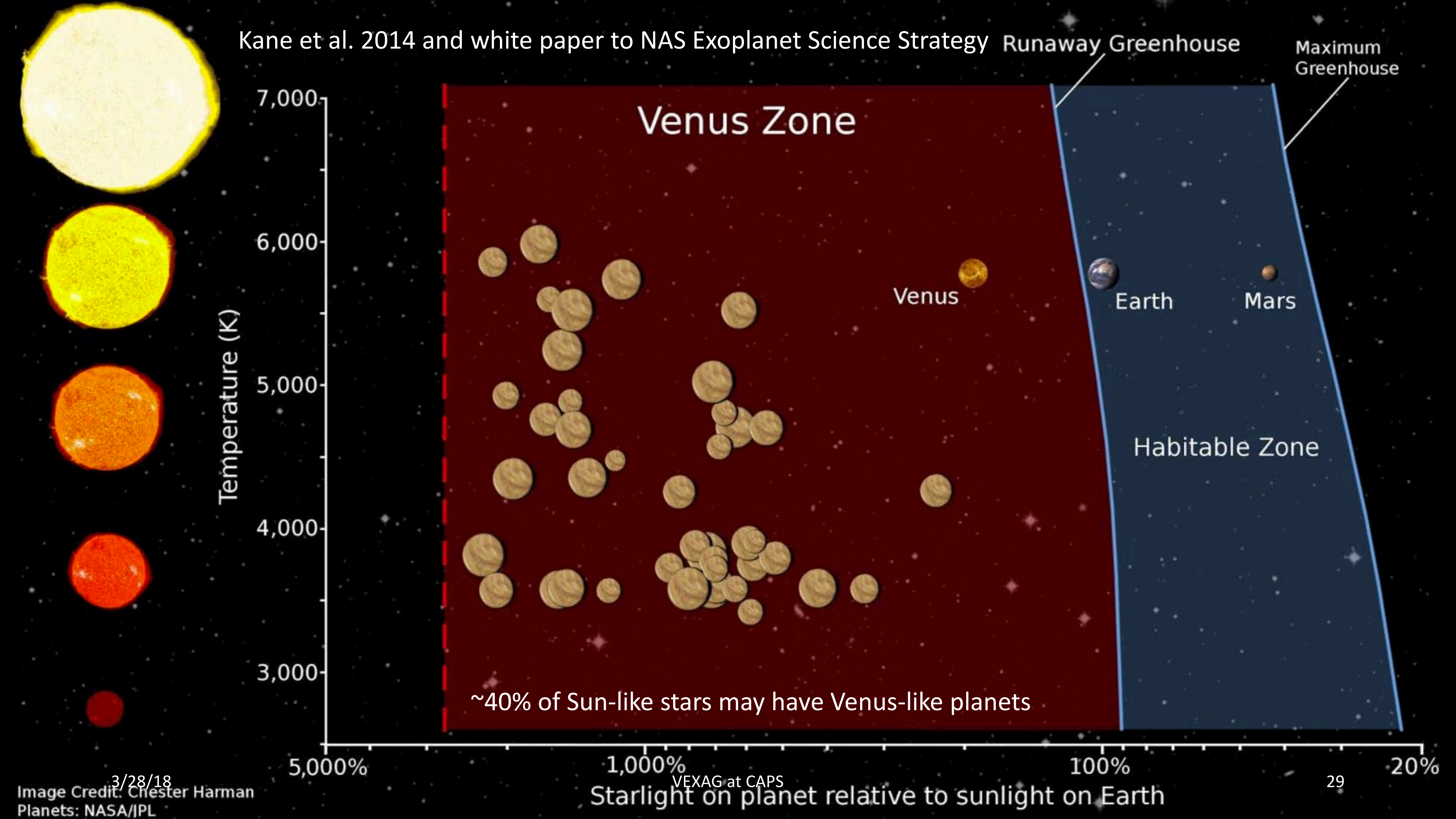
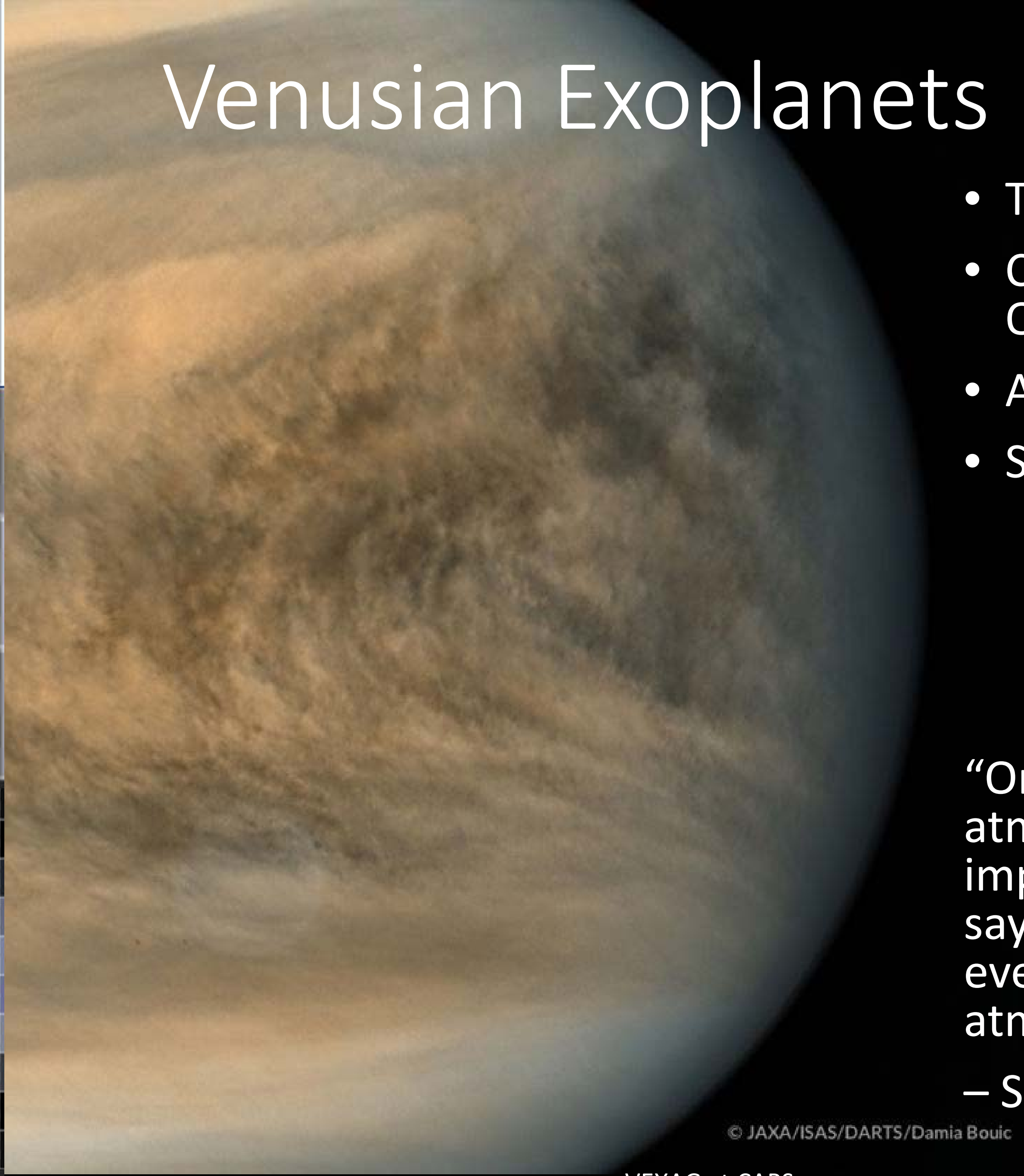


Image Credit: JPL

Kane et al. 2014 and white paper to NAS Exoplanet Science Strategy





Venusian Exoplanets

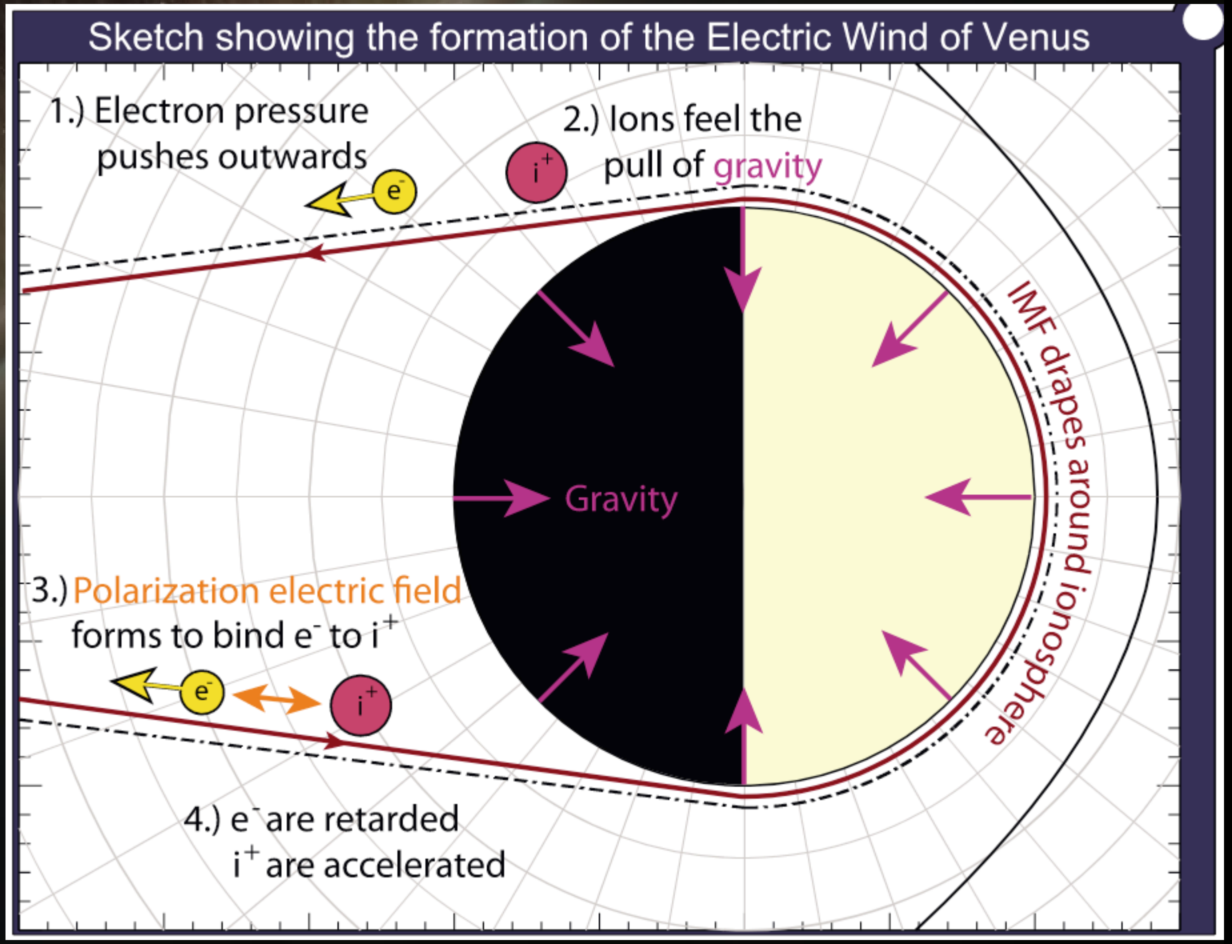
- Temperature
- Clouds - CO_2 spectrum (H_2O? Other?)
- Atmosphere Variability
- Star-Planet Interactions
    - Atmosphere – Stellar Wind
    - Atmosphere ablation

"Once you break a planetary atmosphere…[it's] almost impossible to unbreak," Kane says. "Venus could be the eventual outcome of all atmospheric evolution."

– Stephen Kane

How are oceans lost?

- Idea has been early loss followed by solar wind stripping of light elements
- VEx shows primary species escaping in Venus plasma tail are H and O ions in water-like ratio of 2:1 [Svedhem et al.,2009]
- Collinson et al. [2016] measured "electric wind" about Venus 5x Earth which facilitates loss of ions <18 amu



Collinson et al. 2016

The discovery of a powerful electric wind at Venus, an Earth-like terrestrial planet, also has important consequences for the study of exoplanets by missions such as Kepler. If, for example, the electric potential drop in Earth's (or another Earth-like planet's) ionosphere was a Venus-like +12 V, then a similar direct loss of heavy ions would likely occur, regardless of the presence or absence of a planetary dynamo magnetic field, leading to higher rates of loss. Significant changes to planetary escape rates could impact the ability of a planet to retain an atmosphere [*Zahnle and Catling*, 2013; *Cohen and Glocer*, 2012] and maintain liquid water oceans and increase the likelihood that a planet loses its oceans during the moist greenhouse phase [*Chassefière*, 1997]. Such a strong escape mechanism could also impact the redox evolution of a planetary surface [*Caitling et al.*, 2001]. Given that we believe Venus' stronger polarization field may arise from its closer proximity to the Sun, and that most known exoplanets have been found relatively close to their stars (since these are easier to detect), the possibility of a strong electric wind must be considered when assessing planetary evolution or the potential for habitability on exoplanets.

THE ASTROPHYSICAL JOURNAL

ATMOSPHERIC CHEMISTRY OF VENUS-LIKE EXOPLANETS

Laura Schaefer and Bruce Fegley Jr

Published 2011 February 4 •

The Astrophysical Journal, Volume 729, Number 1

6. CONCLUSIONS

Based on our surface–atmosphere equilibrium model, we can say that planets similar to Venus (i.e., thick CO_2 atmospheres with only trace water) are more likely to be colder than Venus rather than hotter. Hotter planets should have significantly more water in their atmospheres and generally will have higher total pressures. Hot felsic planets will have relatively large pressures and HF abundances, with less water and HCl than similar mafic planets. Planets colder than Venus are more geochemically plausible. These planets will generally have lower total pressures than Venus and may have water vapor abundances similar or larger than Venus. Cold felsic planets will have higher total pressures, HCl, and HF abundances, but lower H_2O abundances than similar mafic planets.

VEXAG Activities & Agenda

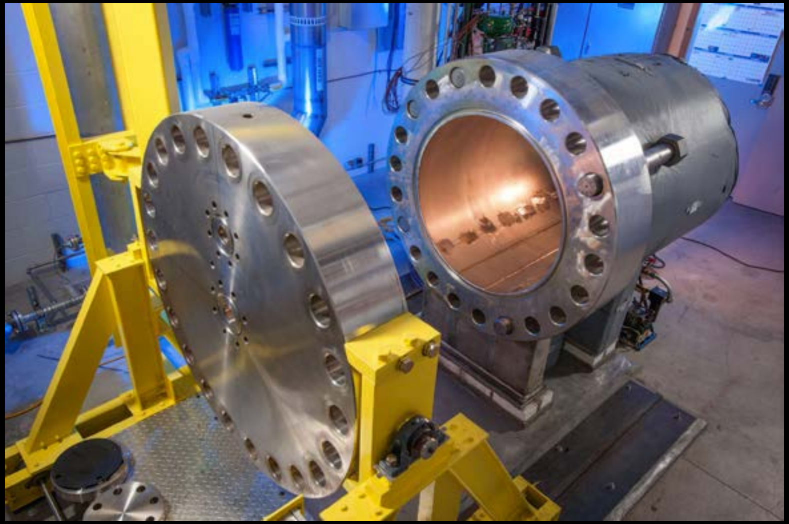
- Identify scientific priorities and opportunities to NASA.
- Develop & update guidance documents
  - Goals, Objectives, and Investigations (GOI) TBR 2018
  - Technology Plan TBR 2018
  - Roadmap TBR 2018
- Propagate priorities to NRC Decadal Surveys (next: 2020)
  - Flagship study 2018-19, white papers 2019.
- Foster next generation of researchers

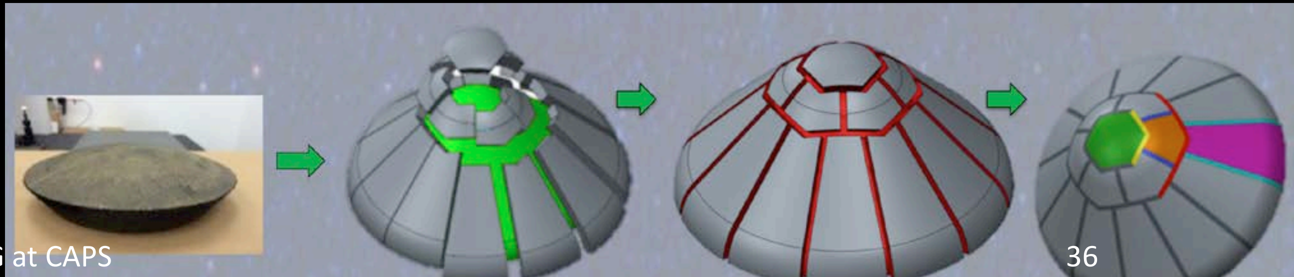
Venus in the 2013 Planetary Science Decadal

- Science Themes
  - *Building New Worlds:* Accretion, water, chemistry, differentiation, atmosphere. Elemental and isotopic species in atmosphere, esp. noble gases and CHNO
  - *Planetary Habitats:* Ancient aqueous environment? Prior habitability, mechanisms of volatile loss, atm. circulation and chemistry, solar-cycle variations.
  - *Workings of Solar Systems:* focus on comparative climatology, plus "myriad processes. "Runaway greenhouse history and implications for Earth, original atmosphere states and coupled interior-atmosphere evolution.
- New Frontiers: Venus In Situ Explorer (VISE) Carryover from 2003 Decadal Survey, but simpler mission profile.
  - Examine physics and chemistry of Venus' atmosphere and crust. Emphasis on characterization that cannot be done from orbit, including detailed composition of lower atm. and elemental & mineralogical composition of surface materials.
- Flagship: Venus Climate Mission (VCM) New mission study at lowest priority among flagships.
  - Investigate atm. origin, CO_2 greenhouse, atmosphere dynamics & variability, surface-atmosphere exchange.
- Requested investments in high temperature technologies

Welcome NASA Investments

- The Hot Operating Temperature Technology (HOTTech) program
- Thermal protection systems Ames Heat Shield for Extreme Entry Environment Technology (HEEET)
- Glenn Extreme Environments Rig (GEER)
- GRC: High temperature SiC systems that enable long-lived surface missions.





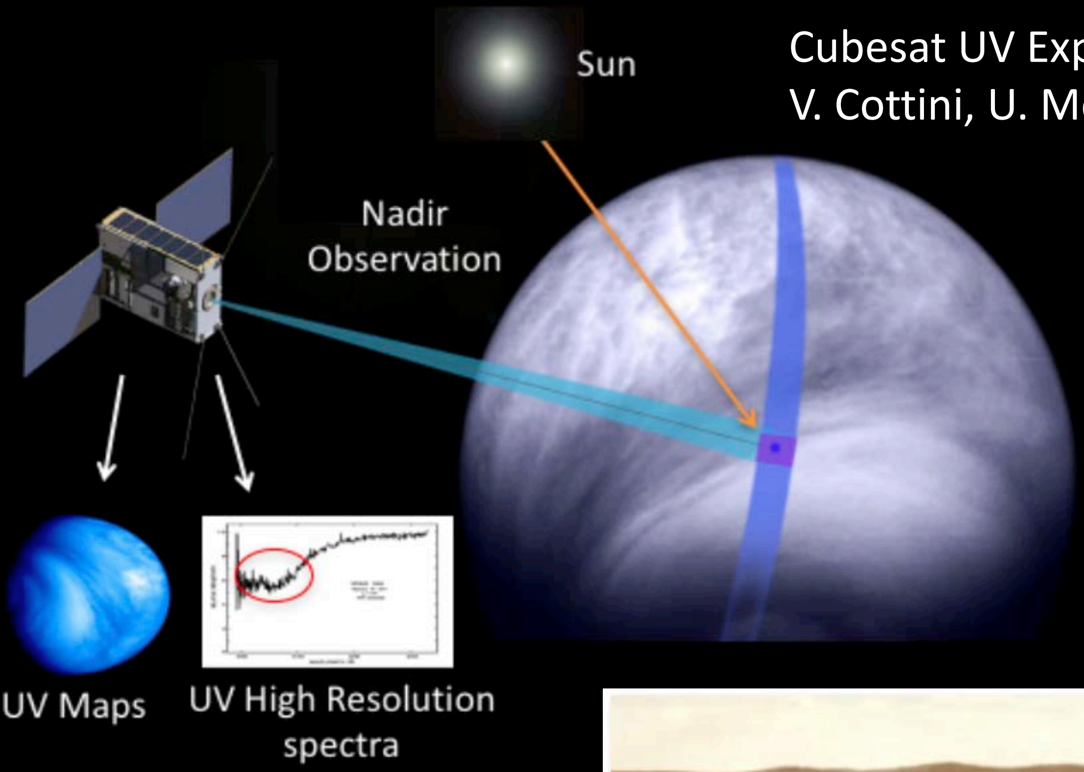
Stackpole et al. 2017

Venus Proposed Missions and Studies

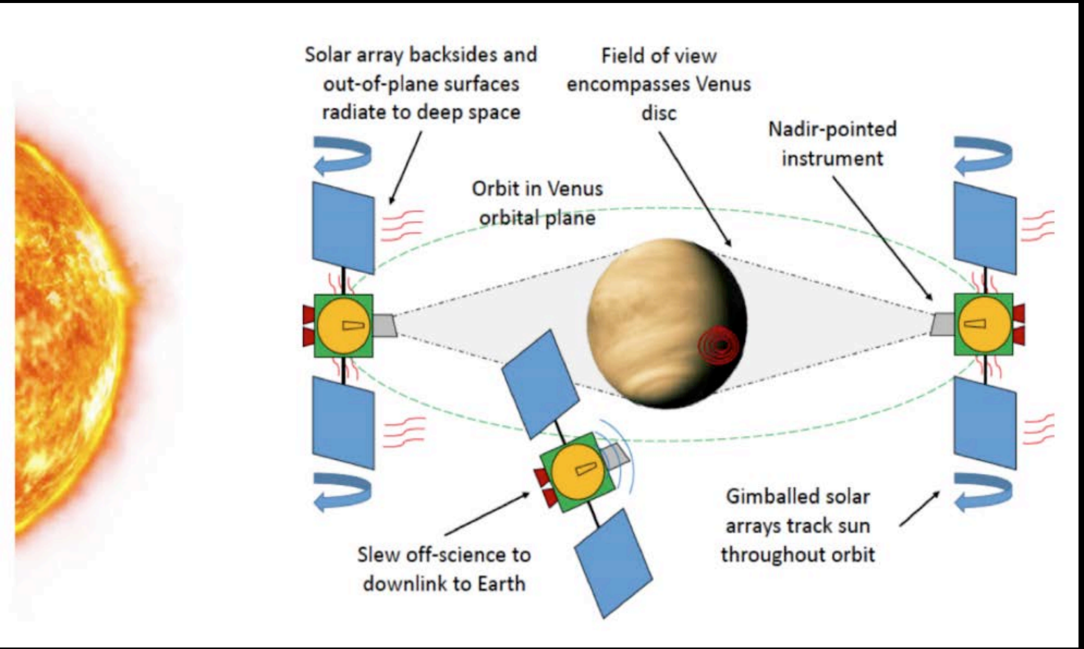
- 2 of 5 Discovery Phase A finalists in 2016 were Venus, but neither selected.
  - NASA assures no bias against Venus
- Three Venus proposals to New Frontiers 2017–none selected for Phase A.
  - VOX was Cat 1
- 4 Venus PSDS3 studies - final reports to be delivered to HQ in March/April
- Venus Bridge study – $200M cap, report to AA in April.
- Flagship study – authorized by HQ for 2018 (GSFC)
- VeGASO (ESA BepiColombo, NASA Parker Solar Probe, ESA Solar Orbiter)
  - Only BC is committed
- Venera-D (Russia) – Joint SDT; include US flight element (aerial platform?); launch 2026 to 2031
  - Pending funding, completion of lunar program, and selection ahead of Phobos.
- EnVision (ESA) – M5 Phase A selections anticipated in May.
- Akatsuki (JAXA) – continues to astound after 2015 rescue, likely ext. into 2021.

Venus SmallSat Concepts

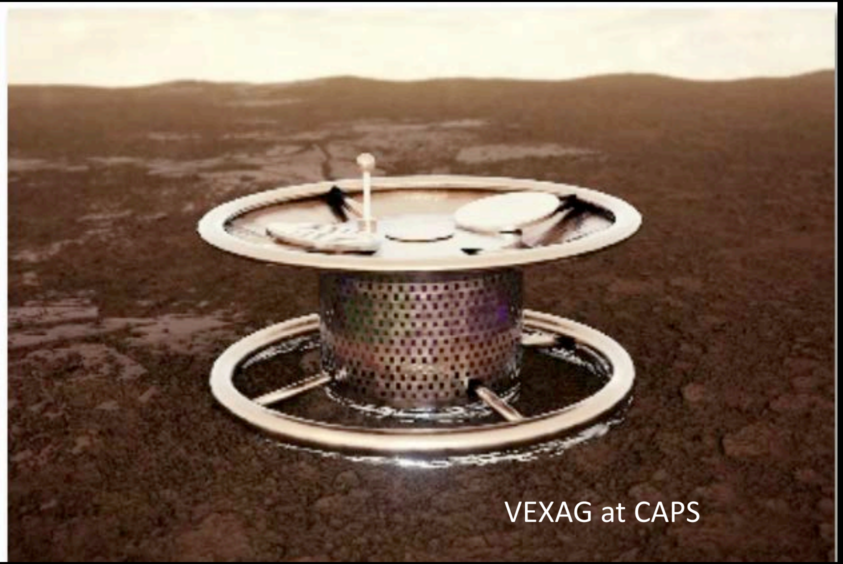
Cubesat UV Experiment
V. Cottini, U. Md

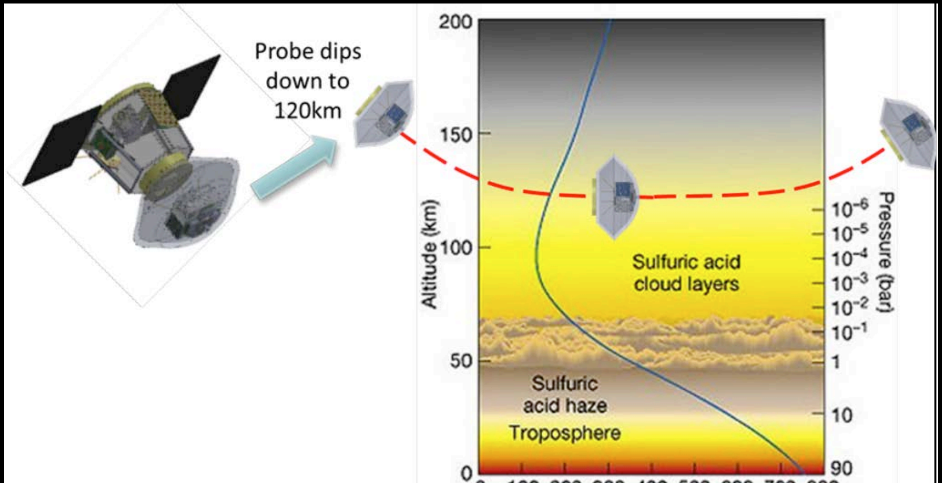


Venus Airglow Monitoring Orbiter for Seismicity
A. Komjathy, JPL



Seismic and Atmospheric Exploration of Venus (SAEVe), T. Kremic, GRC





Cupid's Arrow, C. Sotin JPL

Venus Bridge

- Outcome of AA inquiry "what can you do for $200M?" post-Disco-decision.
- Focus Group convened summer 2017 and assessed useful science and technology architectures likely to fit within nominal cost cap.
  - Decided on linked orbiter + in situ element, launch in early-mid 2020s
- Separate design studies by GRC and JPL
  - GRC: "V-BOSS" orbiter and long-lived lander
  - JPL: 5 orbiter mission types + atmospheric skimmer, probe, or balloon
- Mission concepts include robust, complementary science
- $200M target likely requires some technology development and operations costs outside cap.

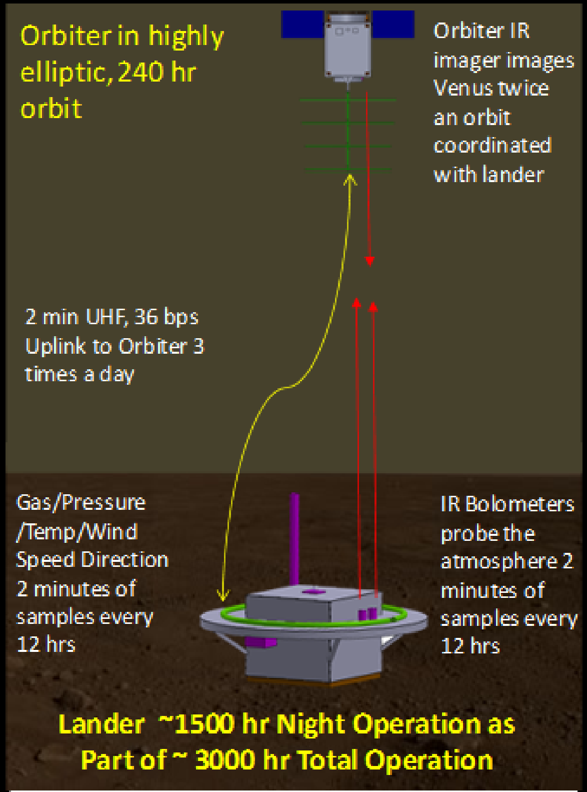


Figure 1: V-BOSS Coupled Orbiter-Lander Concept.

Venus Flagship Study

- Identify science objectives, investigations and mission architectures for a Flagship-class mission to Venus
- Nominal schedule to begin late 2018 and last ~one year
- Report to be ready prior to Decadal Survey scheduled to commence early 2020
- Science Definition Team led by two co-chairs TBD
- SDT membership solicited by NASA and selected with input from co-chairs
- Architecture study will be done at GSFC

A US Venus Program is *essential* to address Decadal Survey goals

40 years

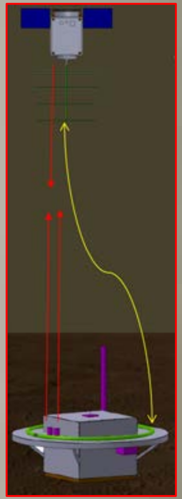
NASA
Magellan
1989-1994

US Missions

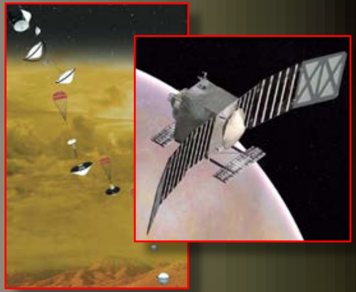
(>30 proposed in Disco & NF)

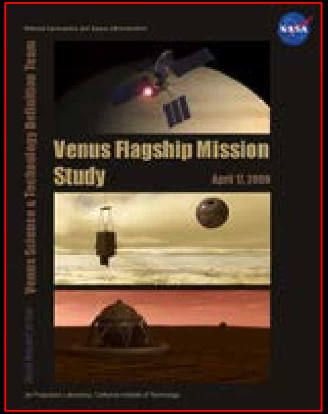
SmallSats?

Venus Bridge
2025?



Discovery
New Frontiers
2026-2028?



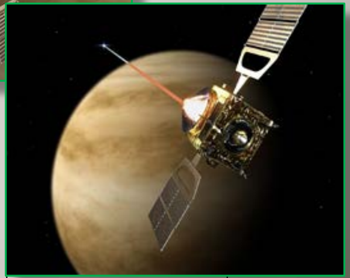


Venus Flagship?

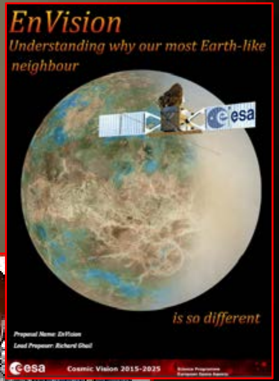
International
Missions

ESA
Venus Express
2005-2014

JAXA
Akatsuki
2010-present



RSA
Venera D
2026+?



ESA
Envision
2031?

1990 1995 2000 2005 2010 2015 2020 2025 2030 2035 2040 2045

We’re Ready to go to Venus

- The Venus community continues to demonstrate the fundamental planetary science that can and must be done at Venus
  - Mature Cat 1 mission concepts in Discovery and New Frontiers
  - Healthy technology development concepts in HOTTECH, PICASSO, MATISSE
  - Innovative papers in the Venus literature and strong conference attendance. Links to planetary habitability and exoplanets.
- The Venus science community is poised with mature mission concepts, intellectual capital, and experience. We must continue to build NASA advocacy and recognition by planetary scientists and the public at large.