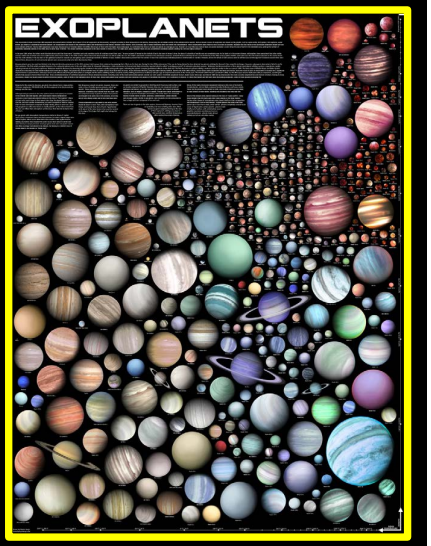
EXOPLANETS IN OUR BACKYARD: WHAT CAN WE LEARN FROM THE TERRESTRIAL PLANETARY BODIES?

(*FINDINGS, SURPRISES AND CAVEATS FROM THE FIRST PHASE OF HUMAN AND ROBOTIC EXPLORATION*)



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The Moon: Pre-1959

What did we know?
What did we not know!

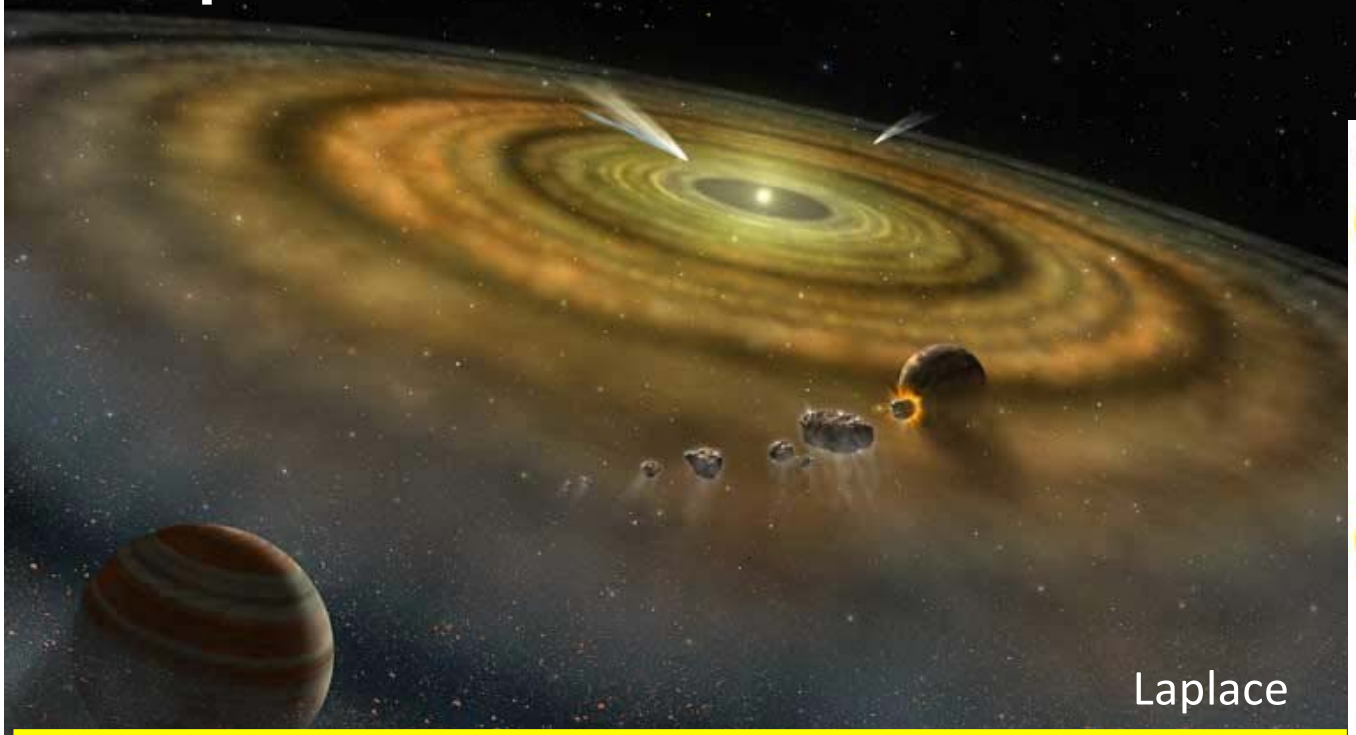
- -Origin?
- -Age?
- -Formed hot or cold?
- -Nature of surface? (Mare and Terra)
- -Age of surface?
- -Origin of craters?

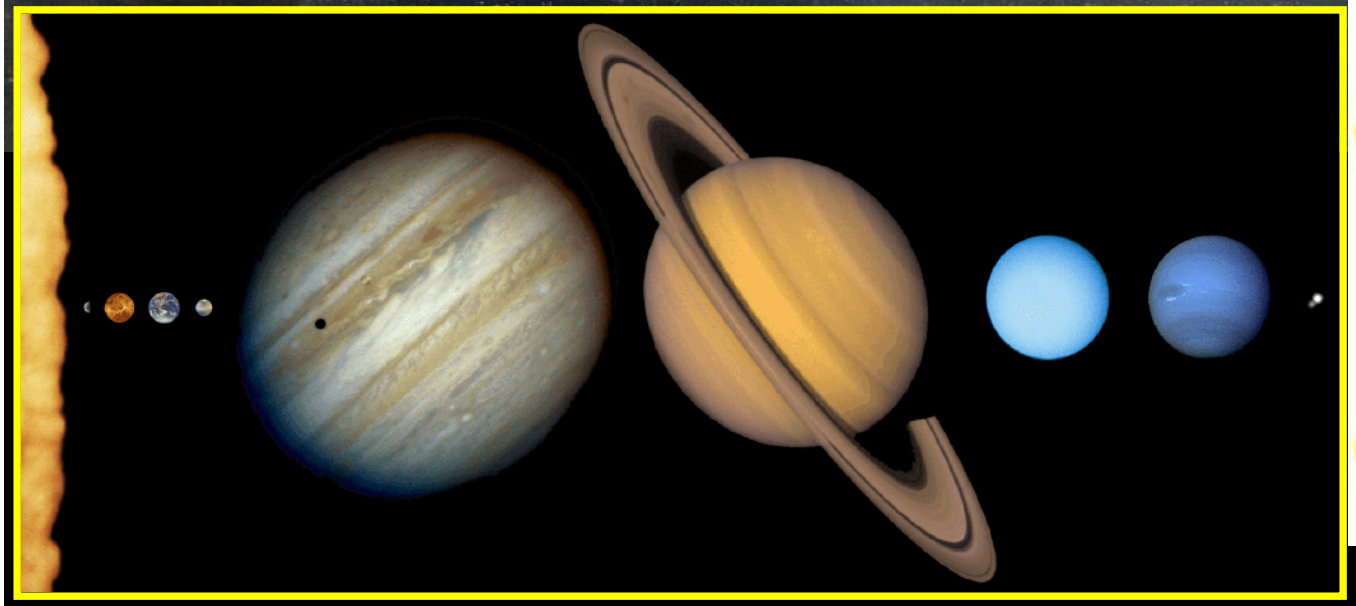
The Moon: Pre-1959

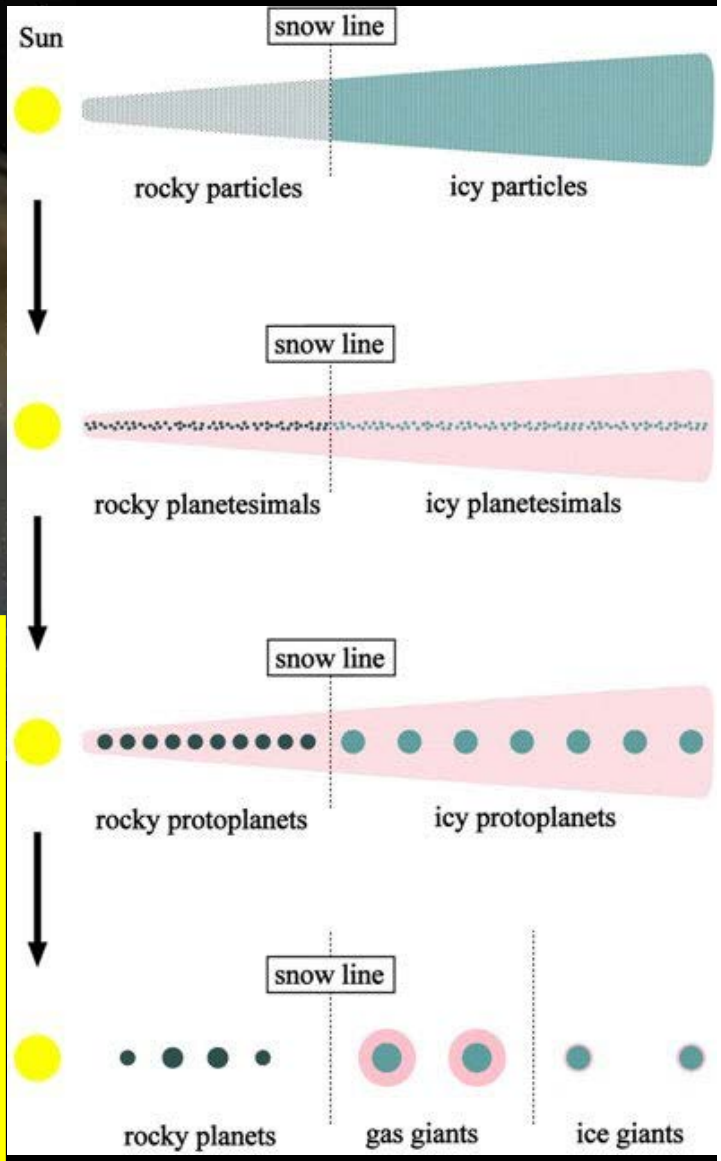
What did we know?
What did we not know!

- -Origin?
- -Age?
- -Formed hot or cold?
- -Nature of surface? (Mare and Terra)
- -Age of surface?
- -Origin of craters?
- ***-What does the other half look like (the lunar farside)?***

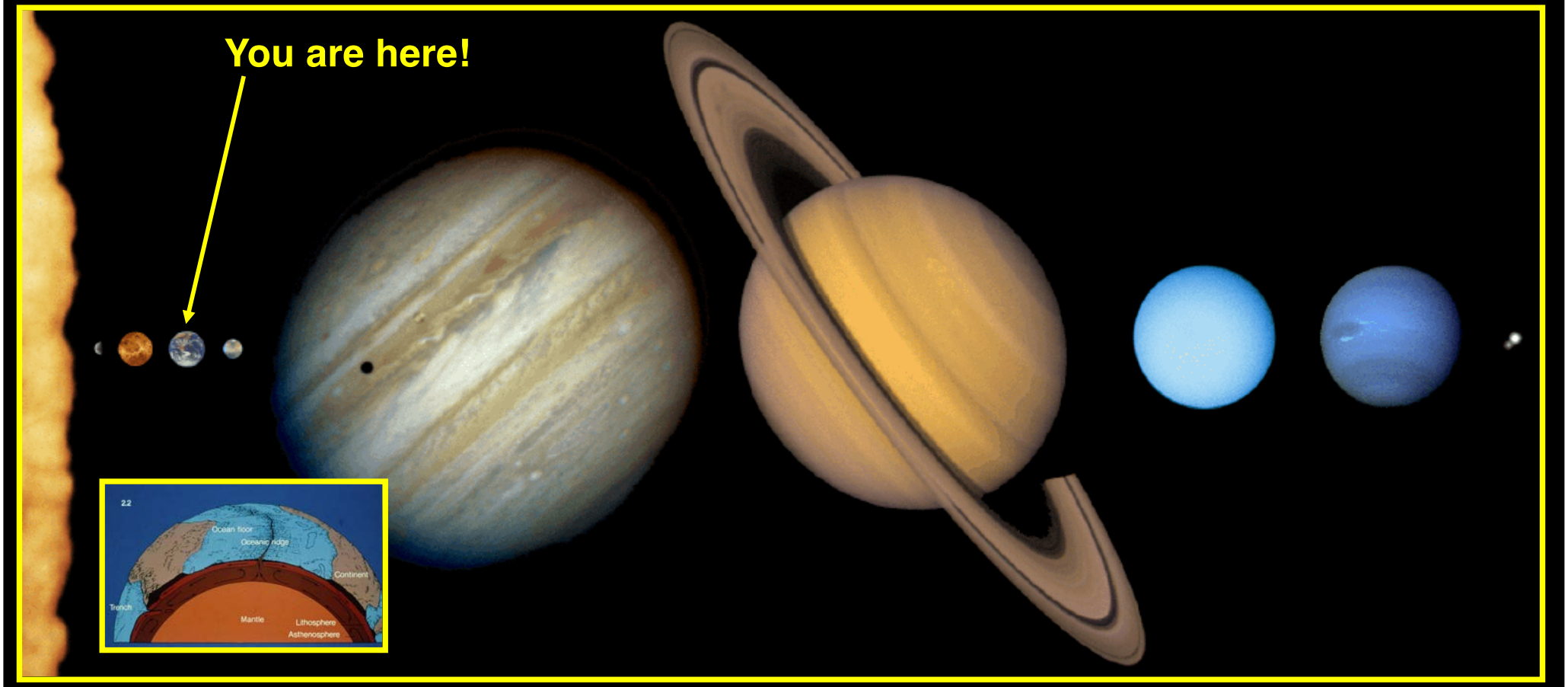
Collapsing Solar Nebula and Planetary Formation
-Temperature and Pressure as a Distance from the ProtoSun-







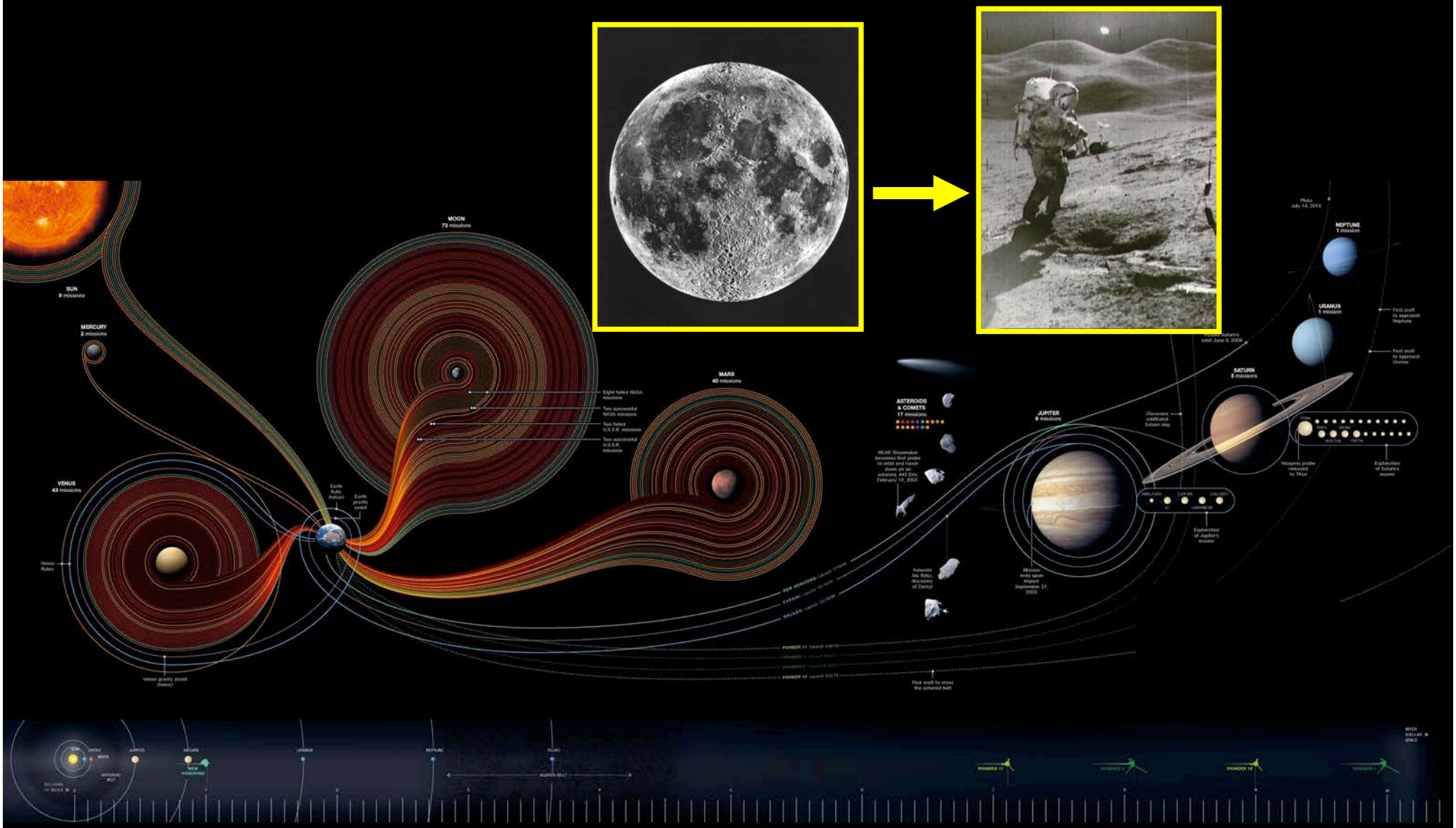
The Earth and the Solar System



Two Parallel Revolutions in Understanding in 60+ years:

1) **Global Plate Tectonics:** *Perception of the Earth as a Planet.*
2) **Space Age:** *The Earth in the Context of the Solar System.*

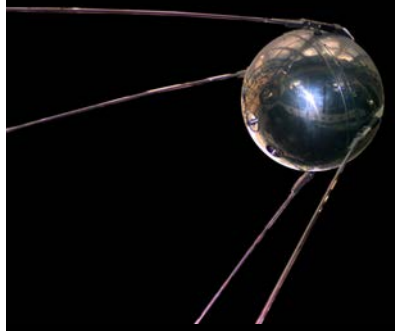
60+ Years of Space Missions



Planets changed from astronomical objects to geological objects!

The Apollo Lunar Exploration Program: Scientific Impact and the Road Ahead

234th American Astronomical Society Meeting: June, 2019



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BROWN

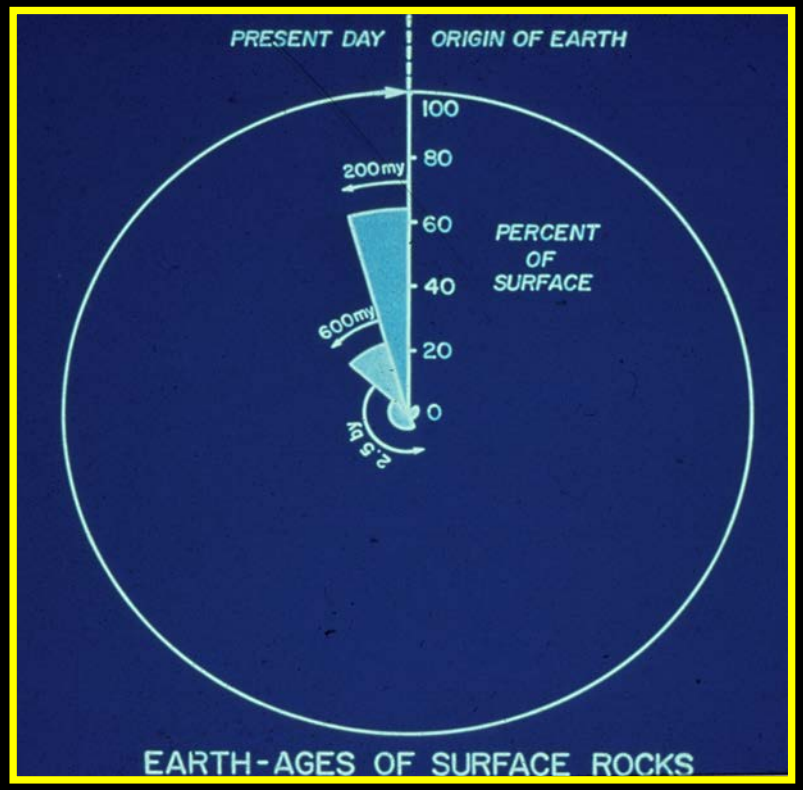
What is the Legacy of Apollo?

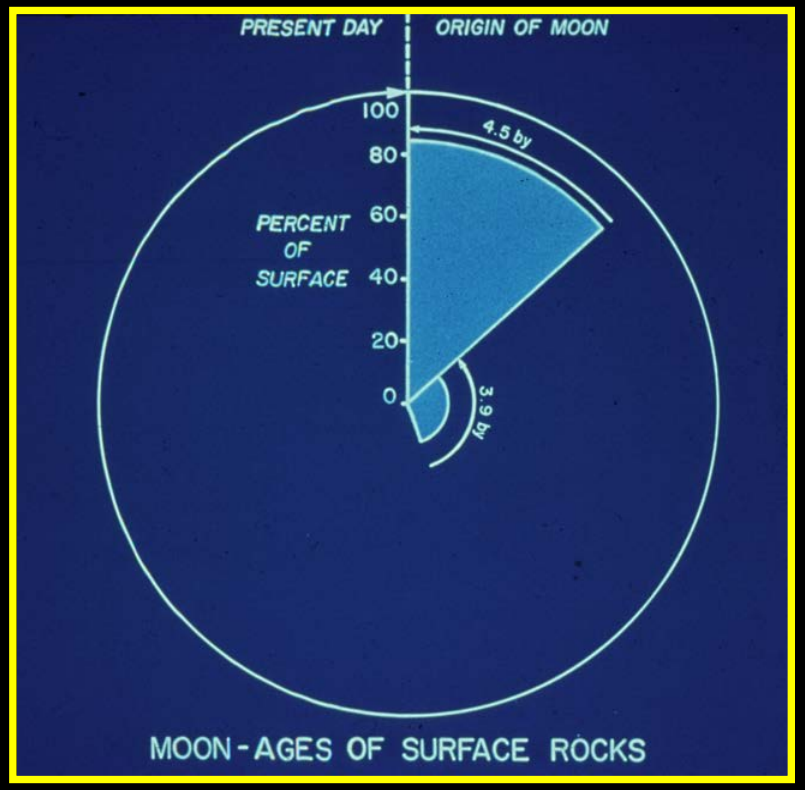
Cornerstone for Understanding Planets!

Earth

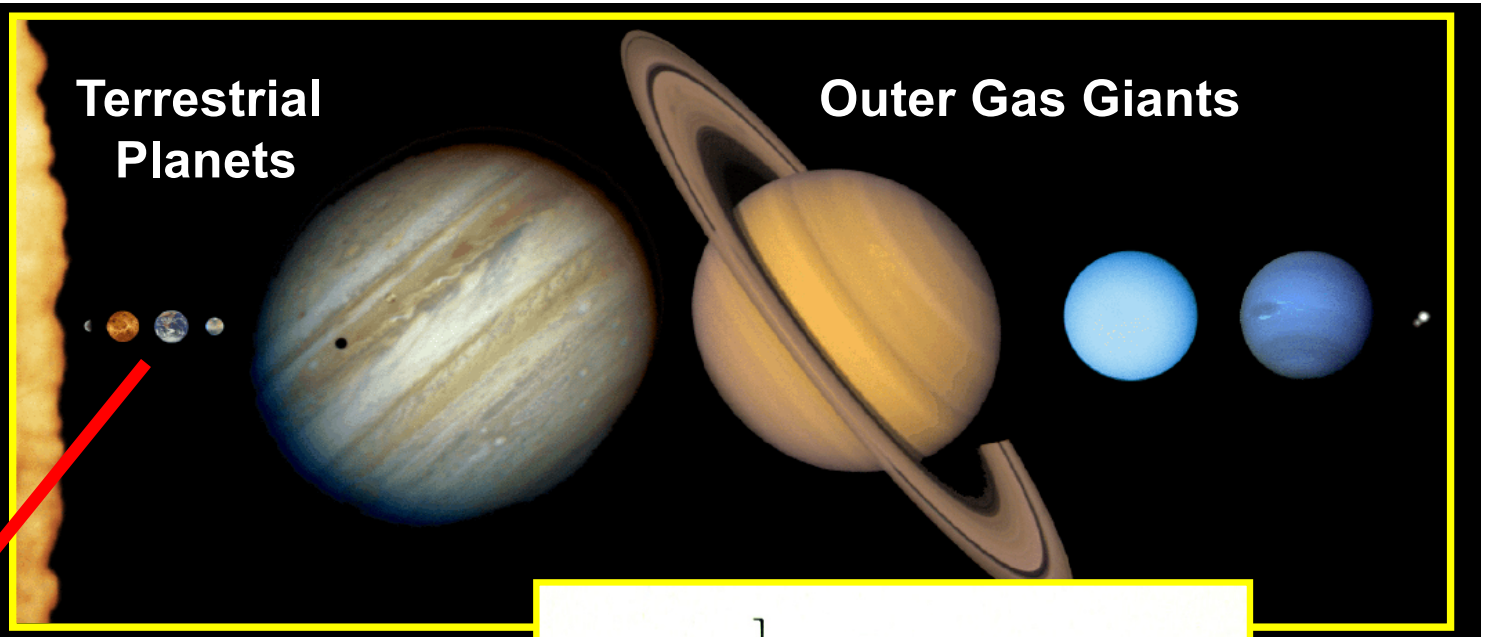
Moon

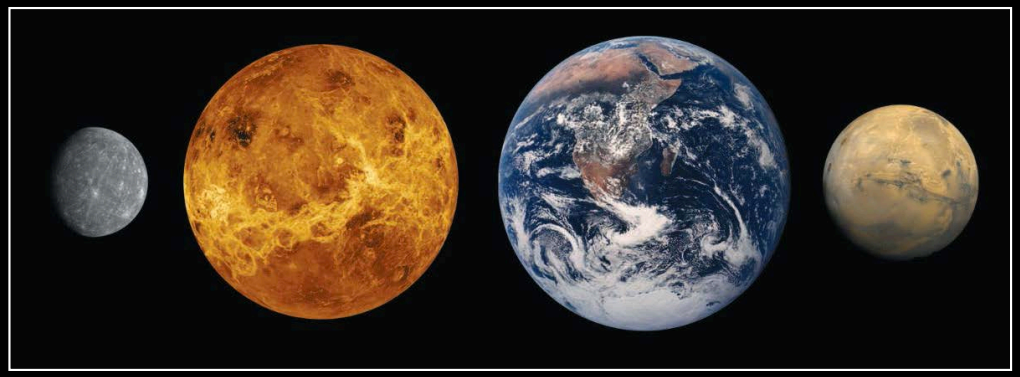
Insights into the Missing Chapters of Earth History



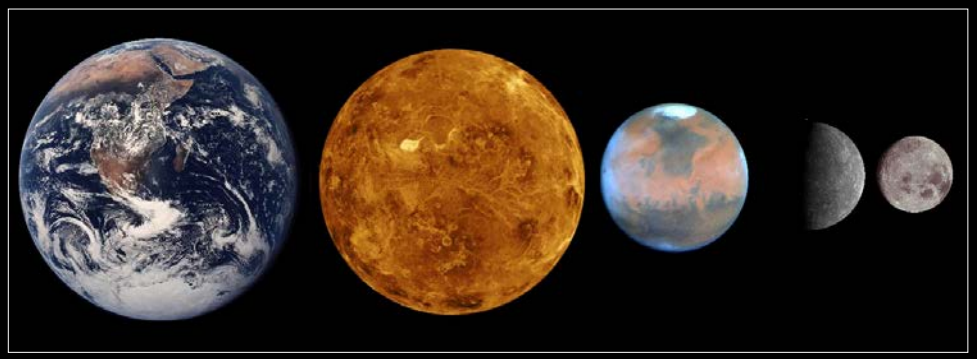


Context of the Terrestrial Planetary Bodies in the Solar System

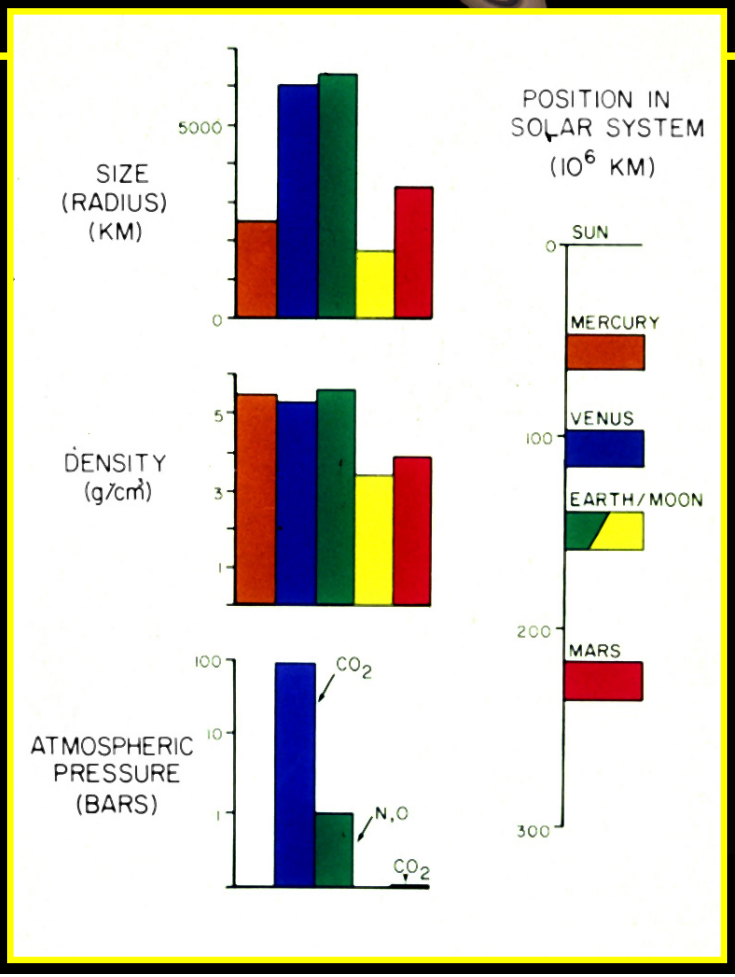




Position



Size



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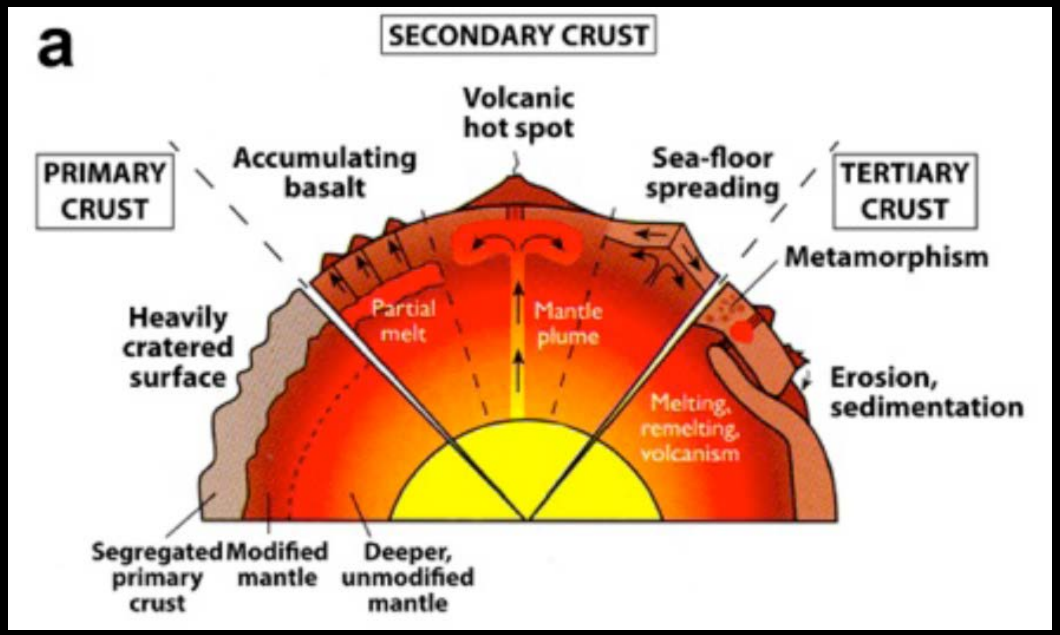
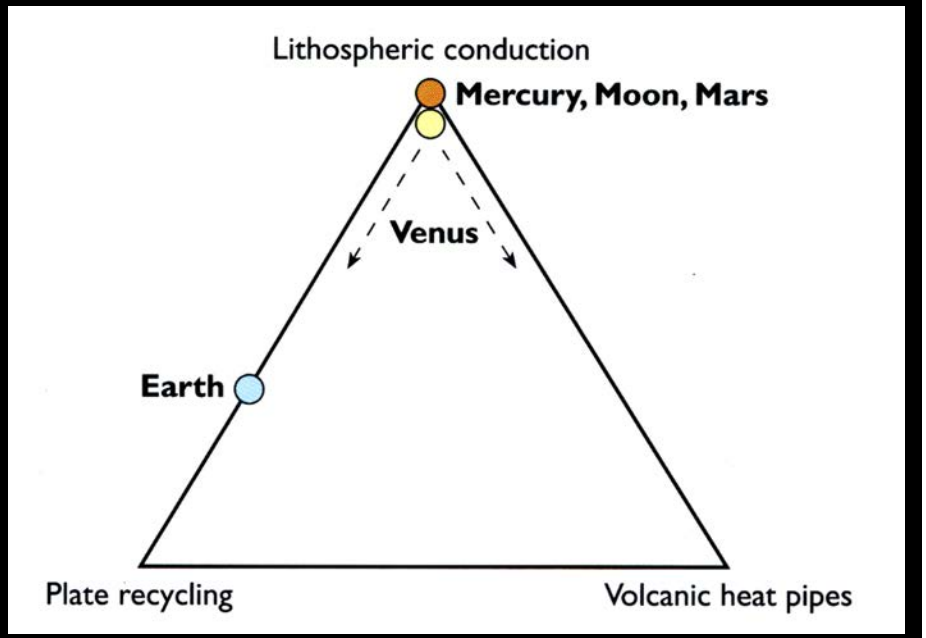
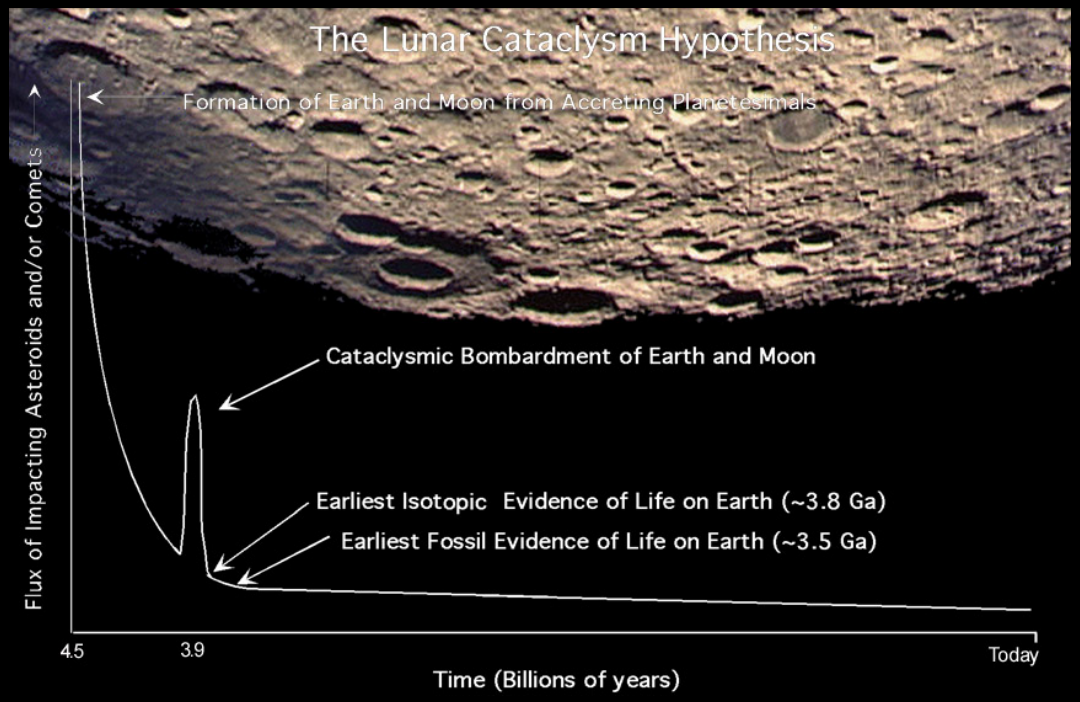
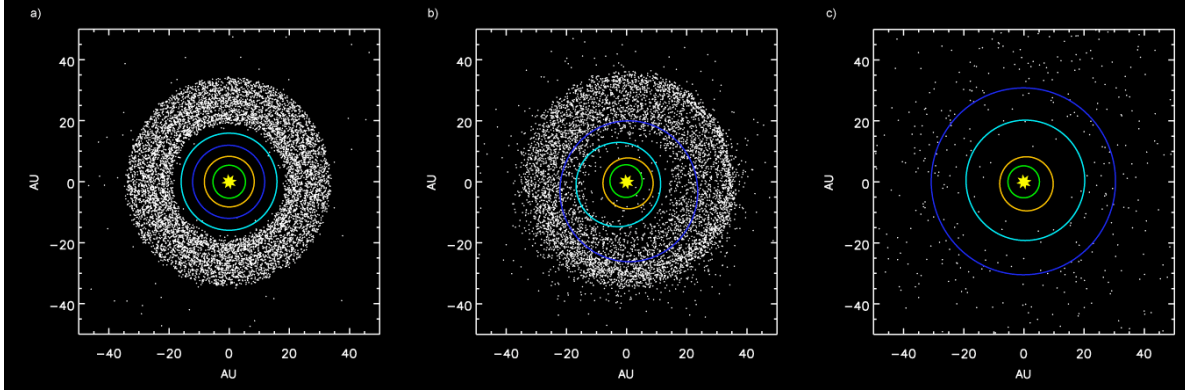




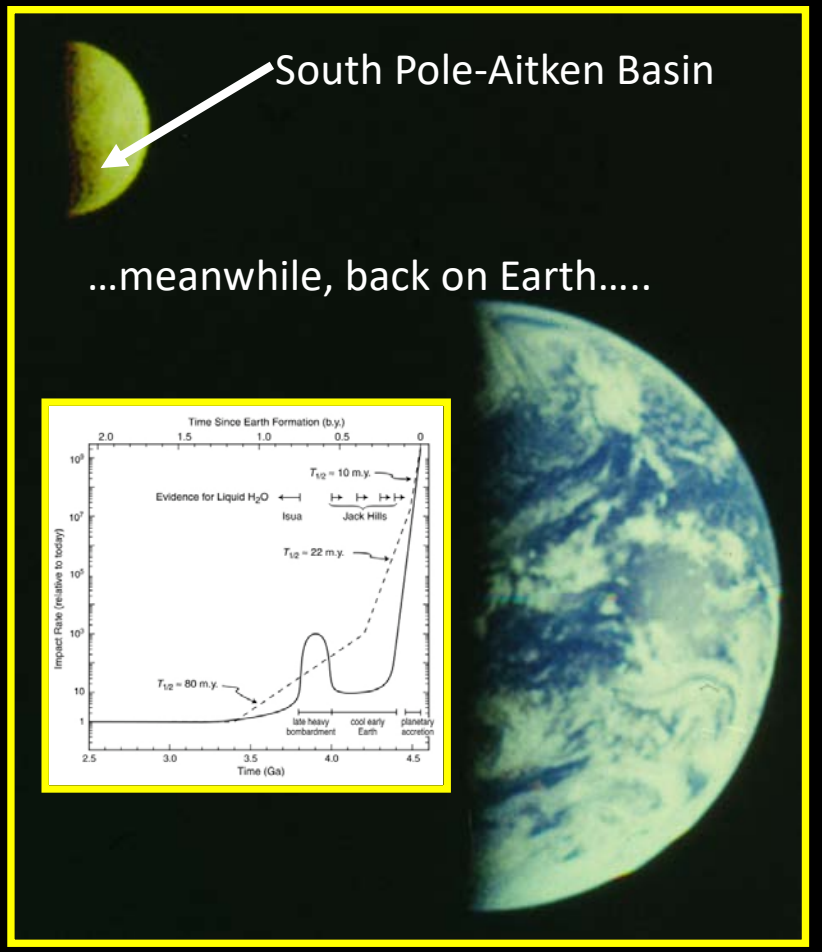
Planets Are Moving Around in Early Solar System History!!!

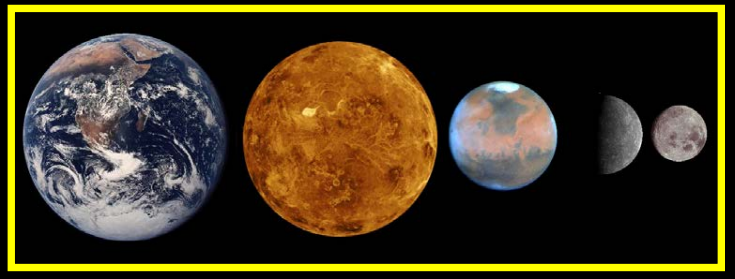


…on the Moon…..



…meanwhile, in the outer solar system…..



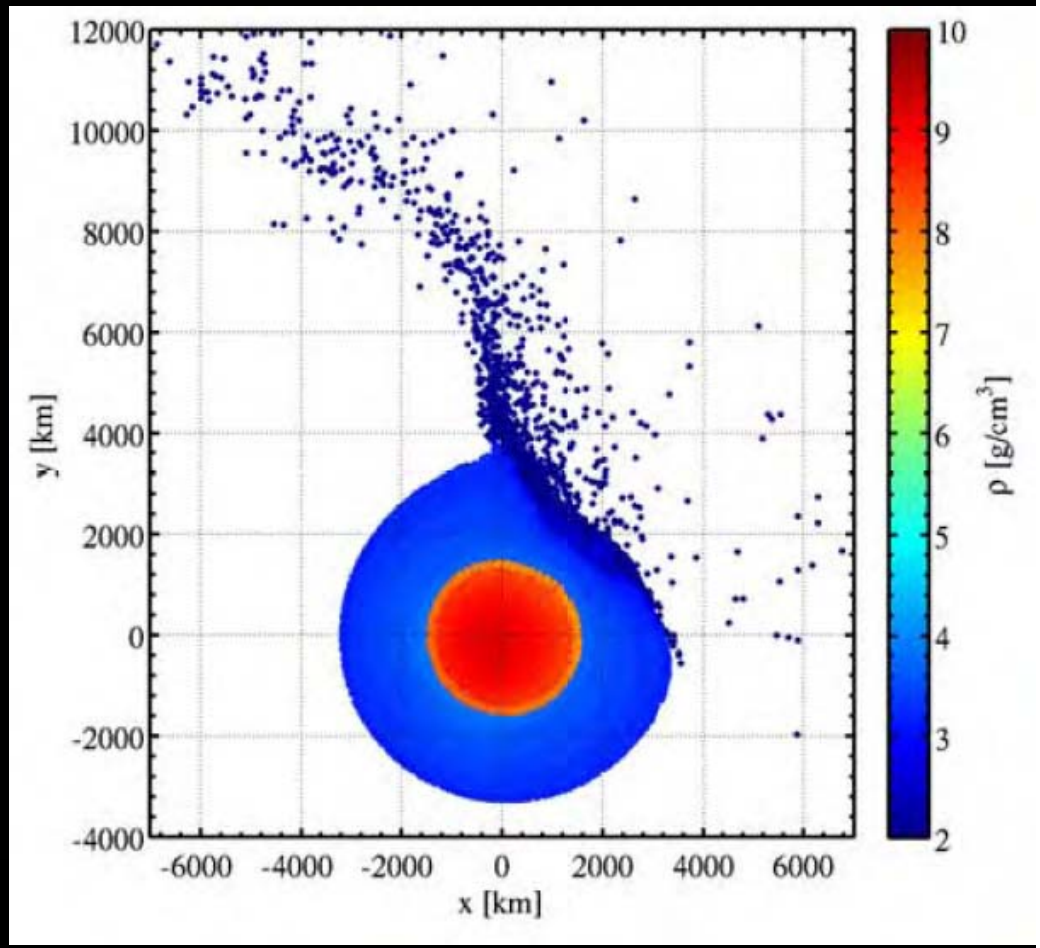


Origin of the Moon: Giant Impact Hypothesis

Mars-size body

Proto-Earth

The Moon is formed due to accretion of impact ejecta placed in Earth orbit by the event.



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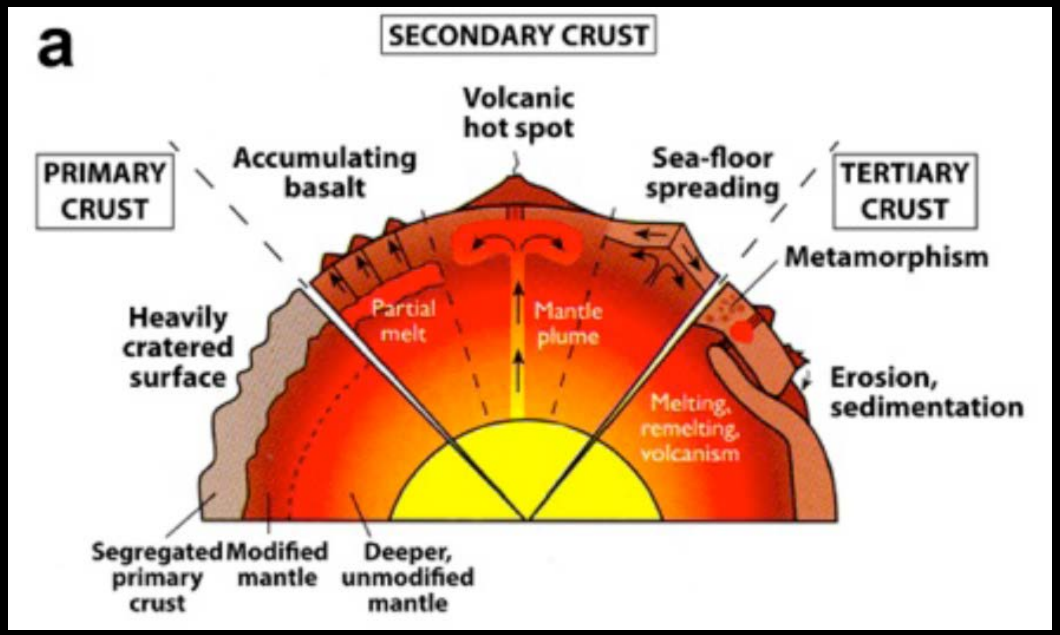

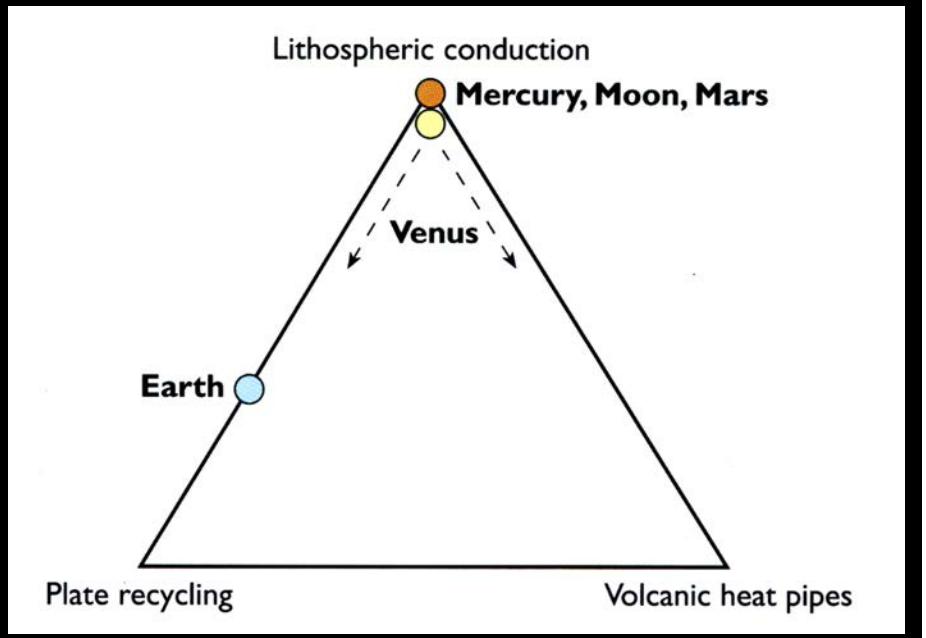

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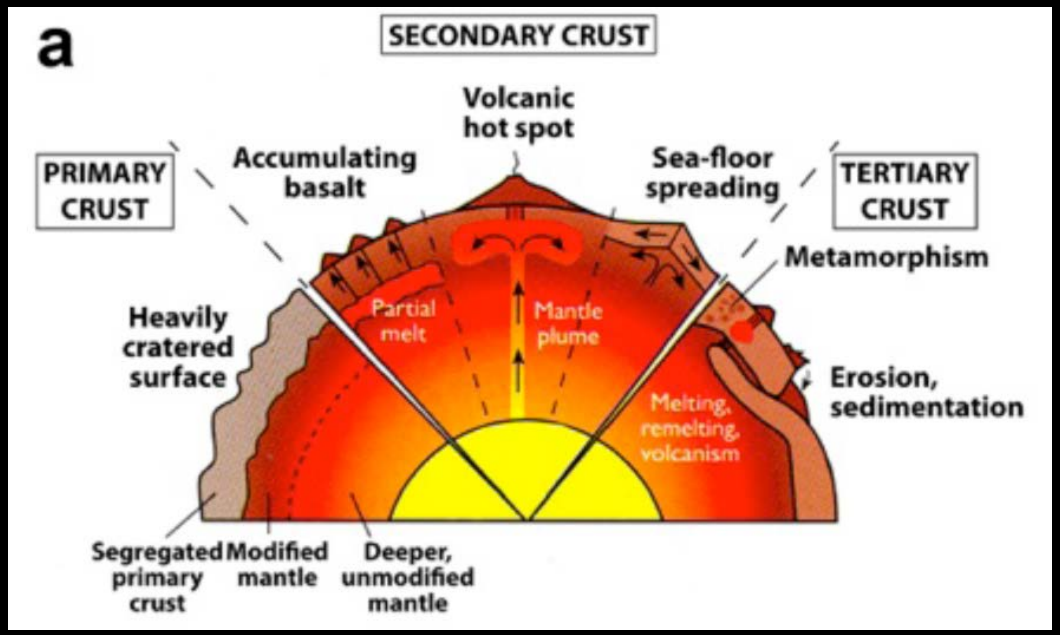
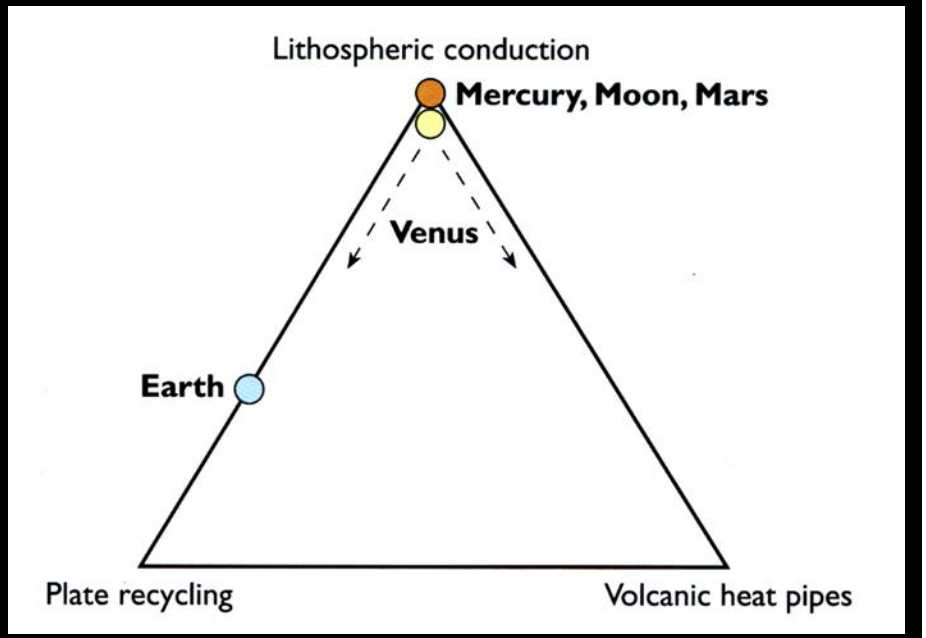
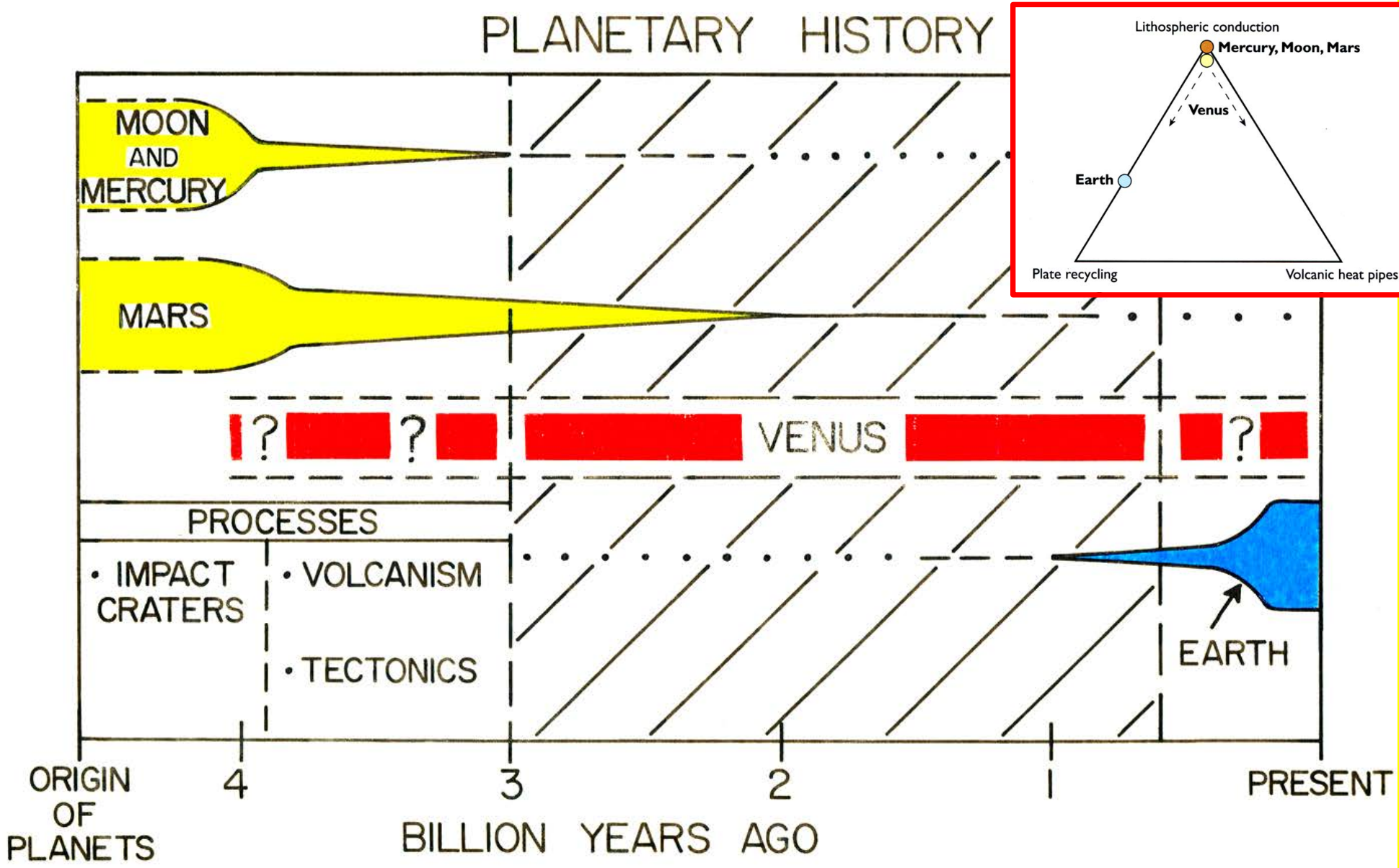
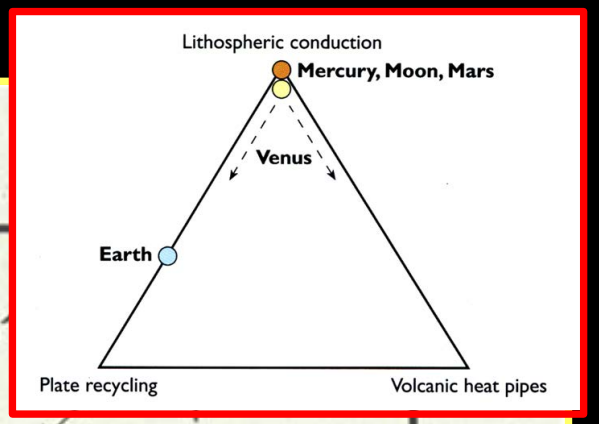




What is the Age of the Surface of Venus?





PLANETARY HISTORY

MOON AND MERCURY

MARS

VENUS

? ?

The first 80% of the History of Venus?

PROCESSES

•IMPACT CRATERS

•VOLCANISM

•TECTONICS

EARTH

ORIGIN OF PLANETS

4

3

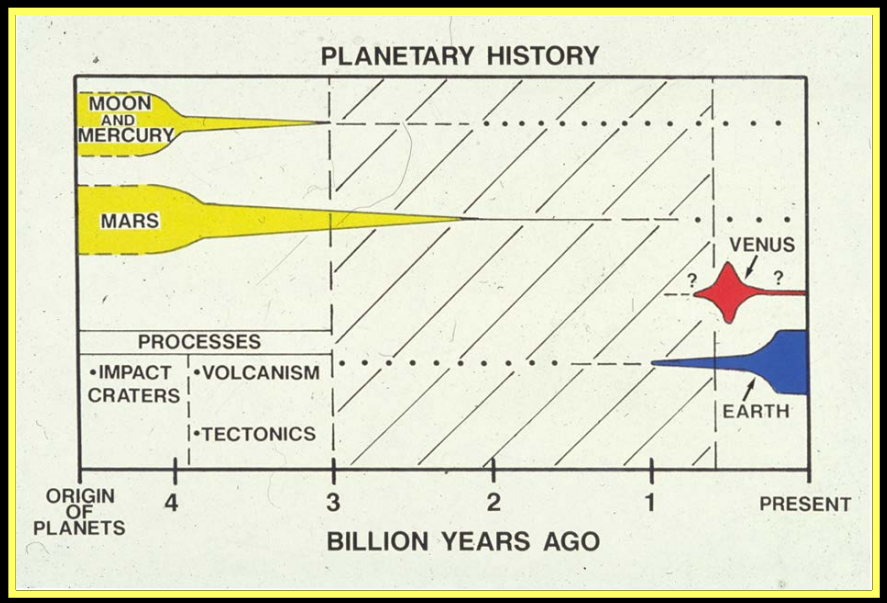
2

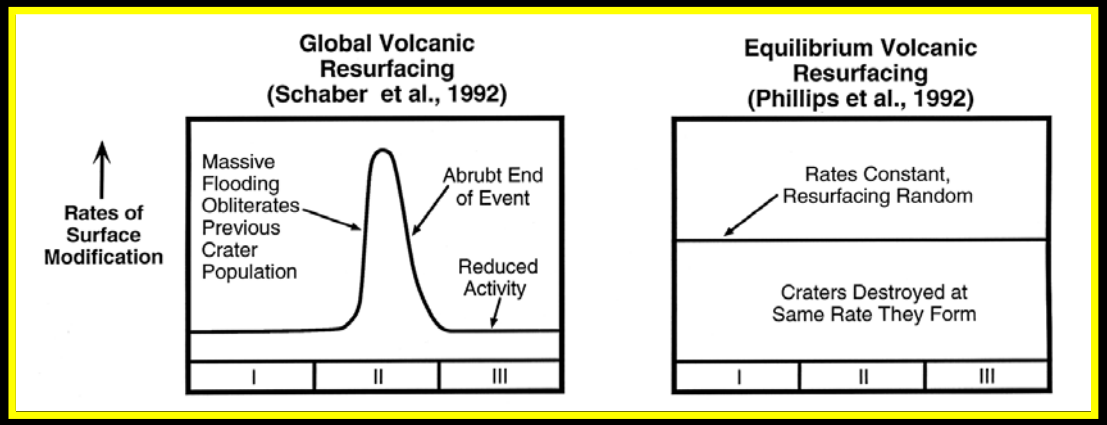
1

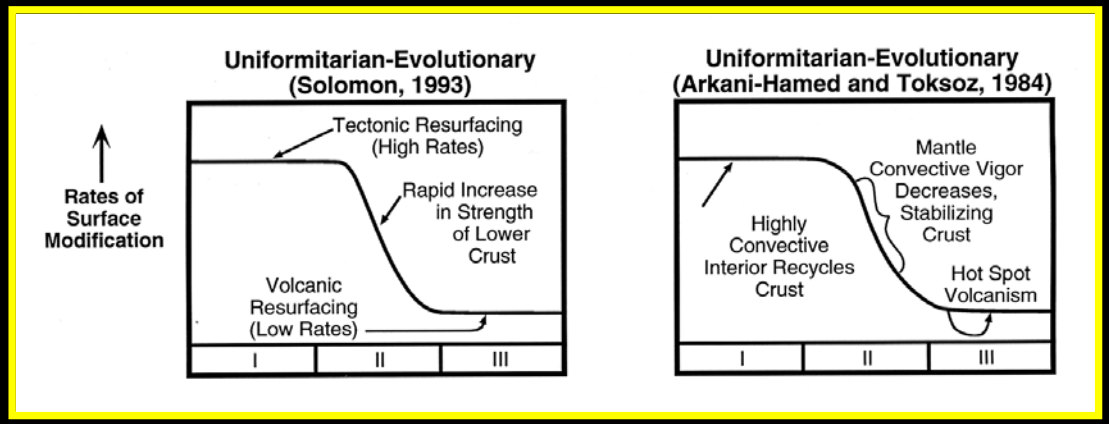
PRESENT

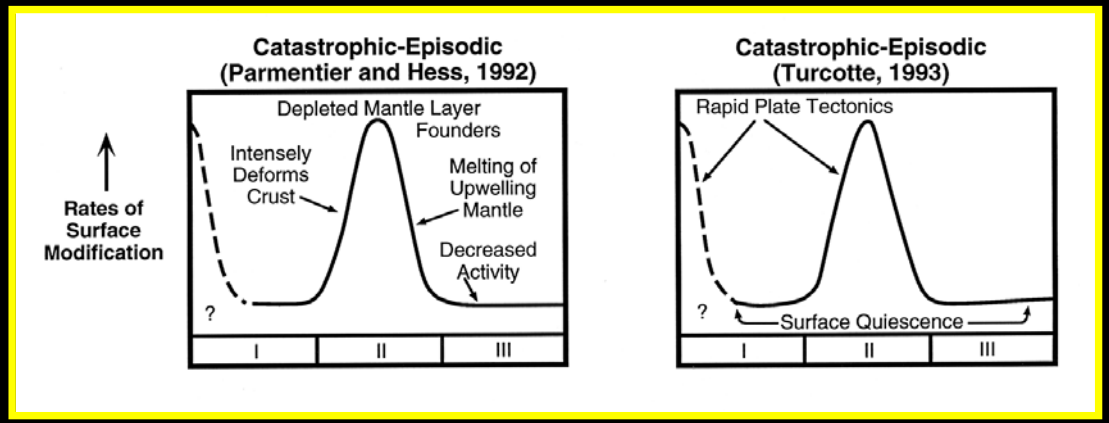
BILLION YEARS AGO

Venus geological record is consistent with a range of *geologically recent catastrophic resurfacing models*.









Models for the Transition from Early to Late History on Venus

Head et al. (2020) **VENUS AS AN EXOPLANET LABORATORY: THE MANY PATHWAYS TO VENUS-LIKE EXOPLANETS AND HOW TO MAKE ENDS MEET**
LPI Cont. 2195, #3053.

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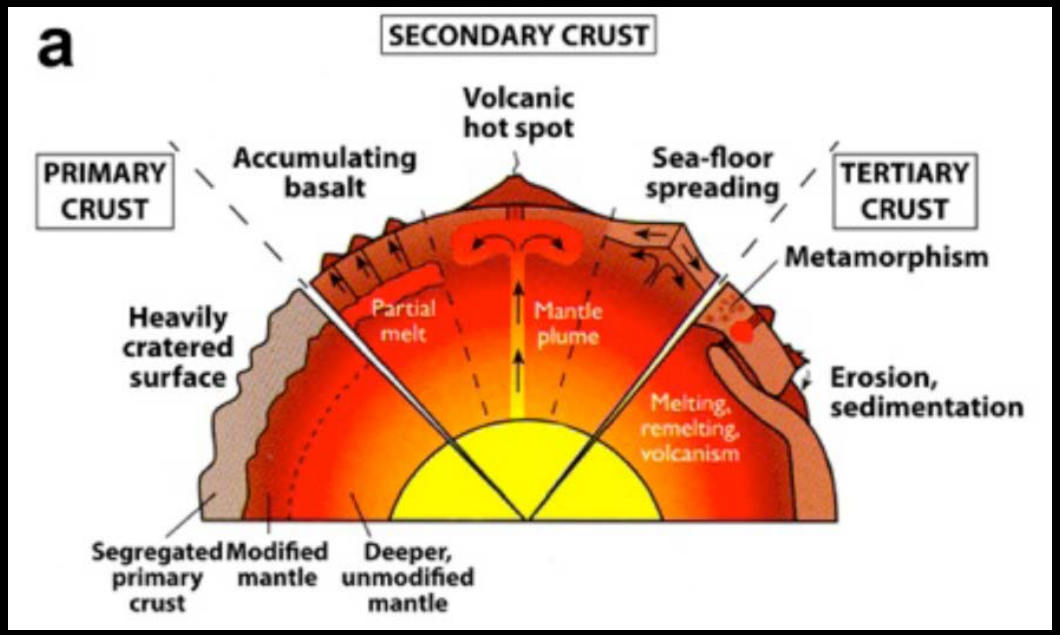

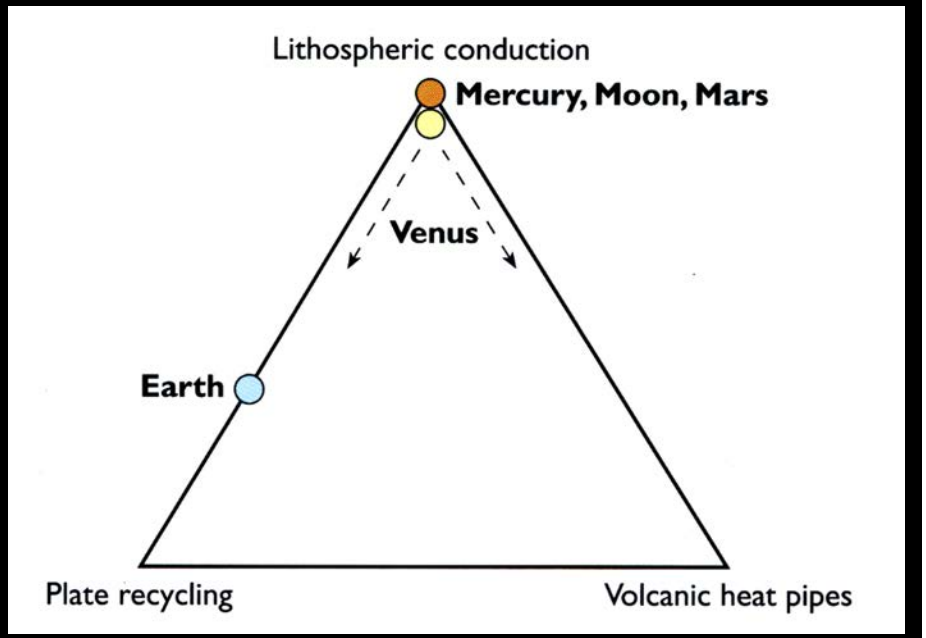

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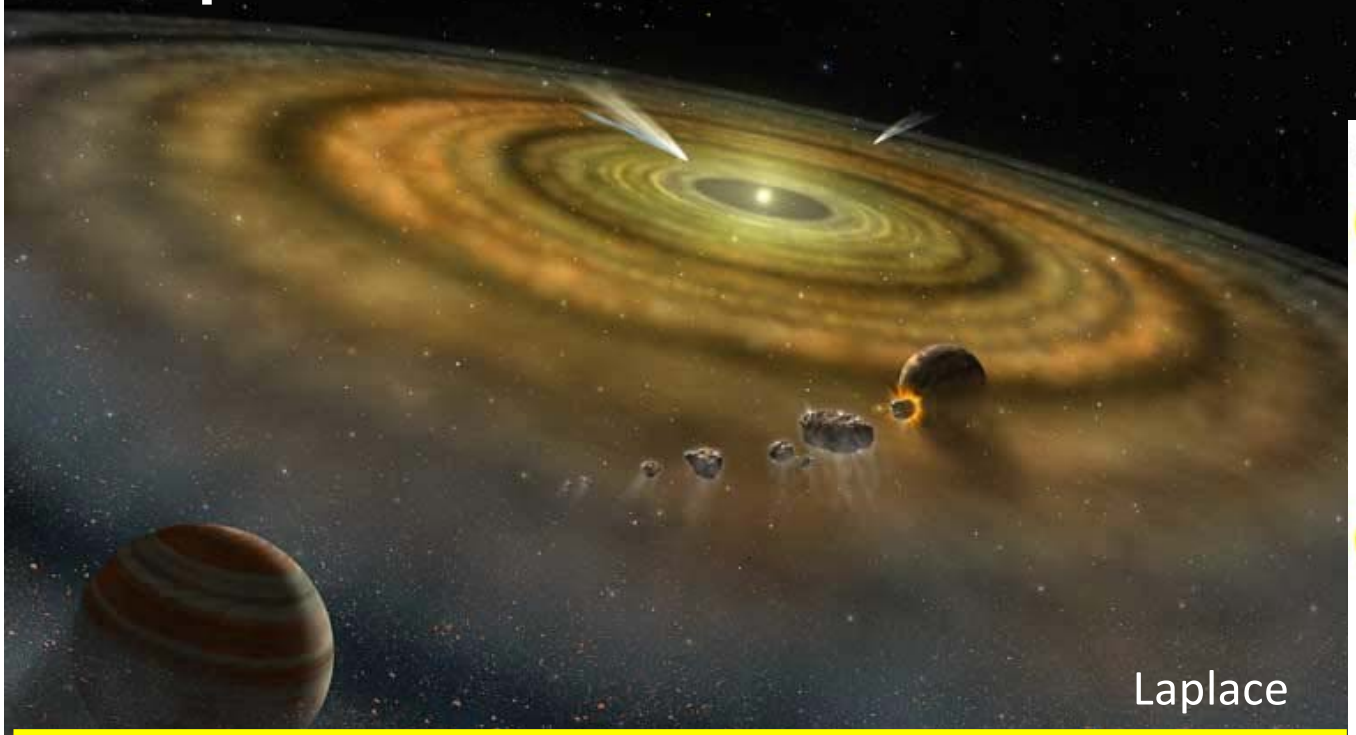
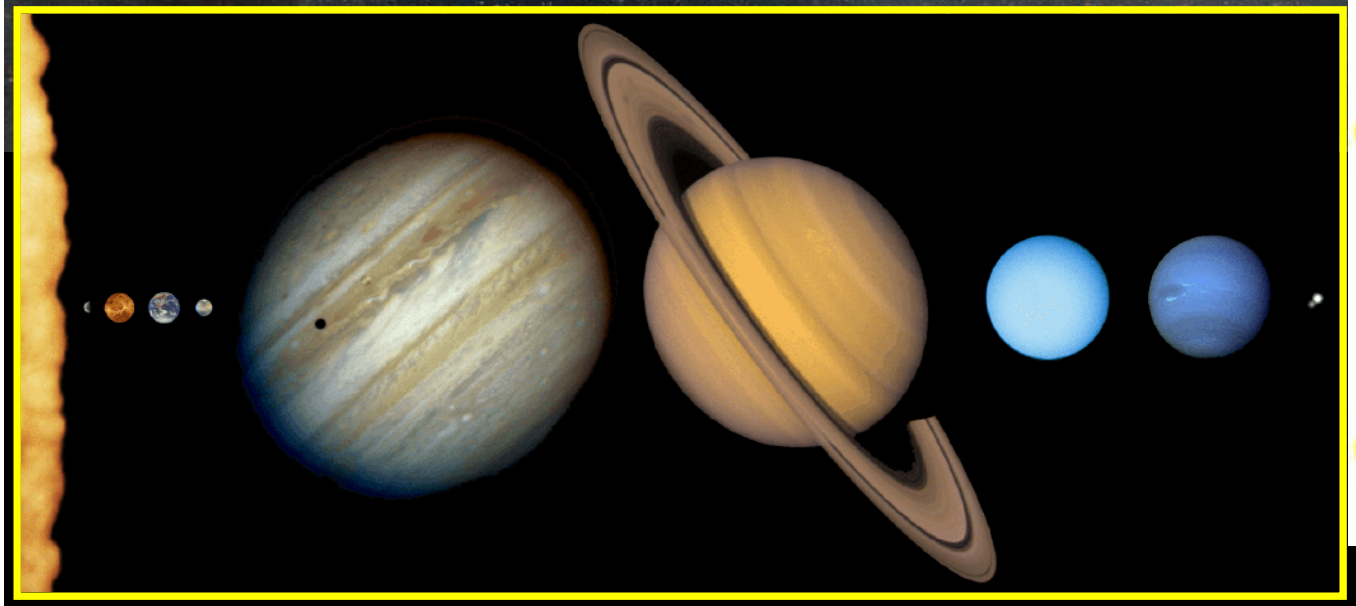
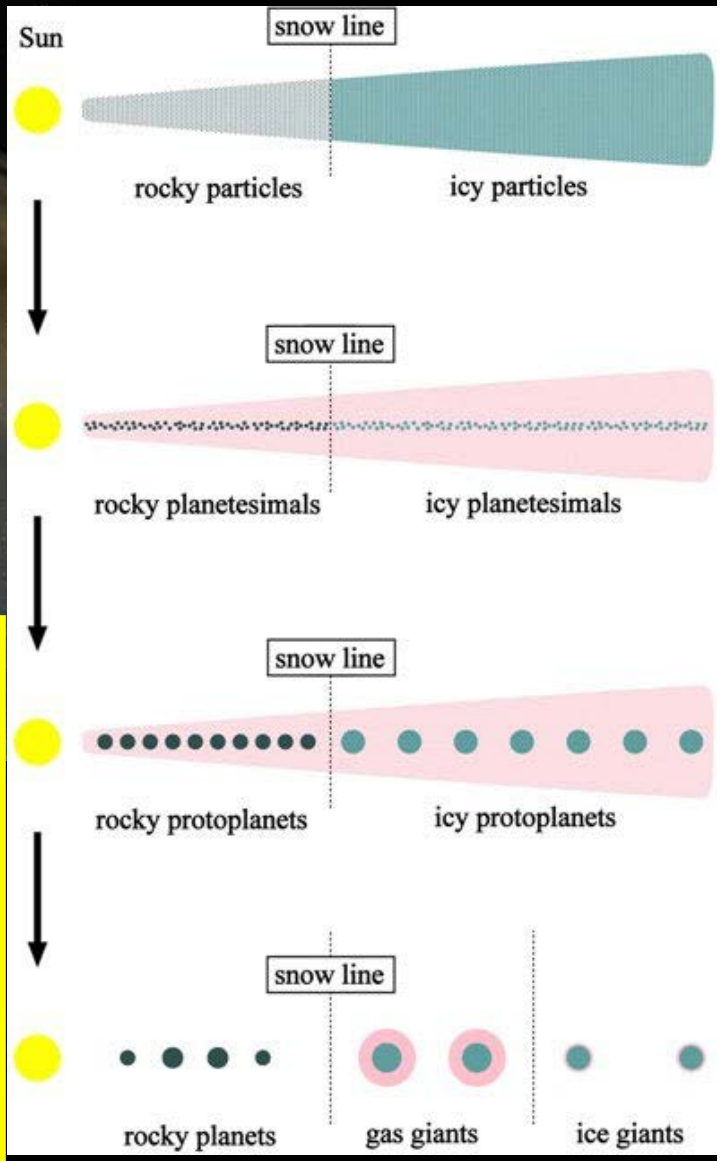
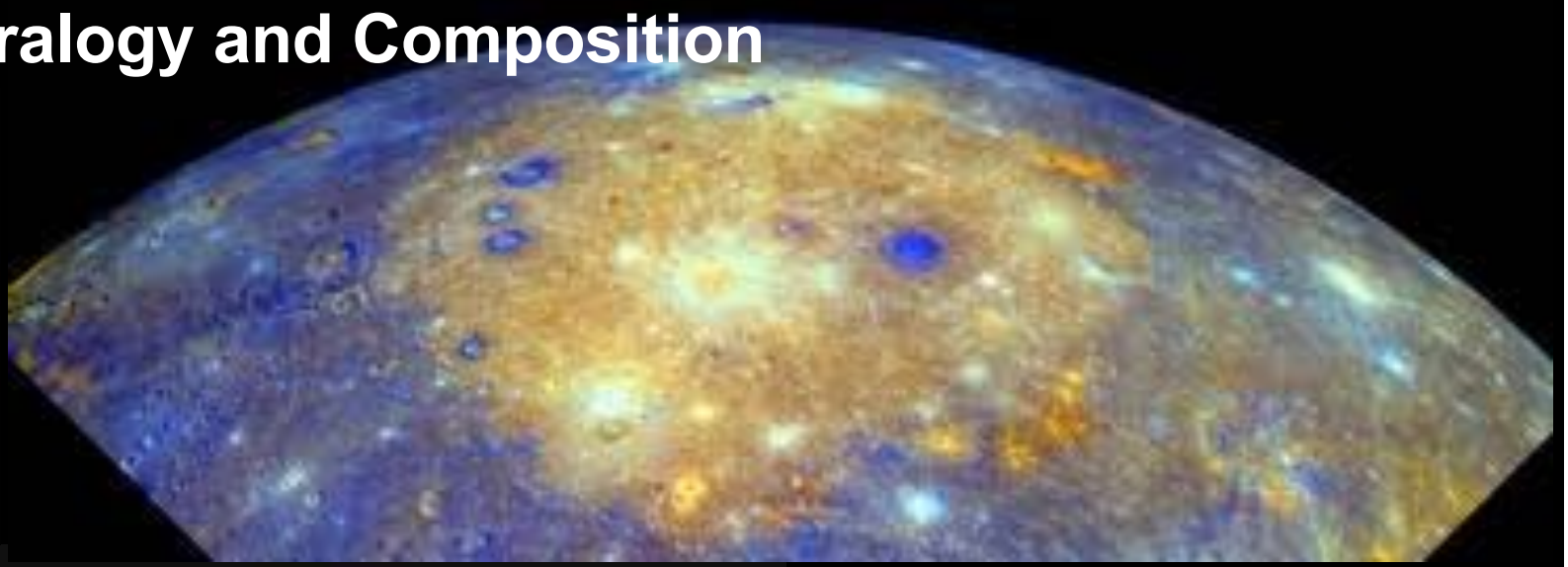
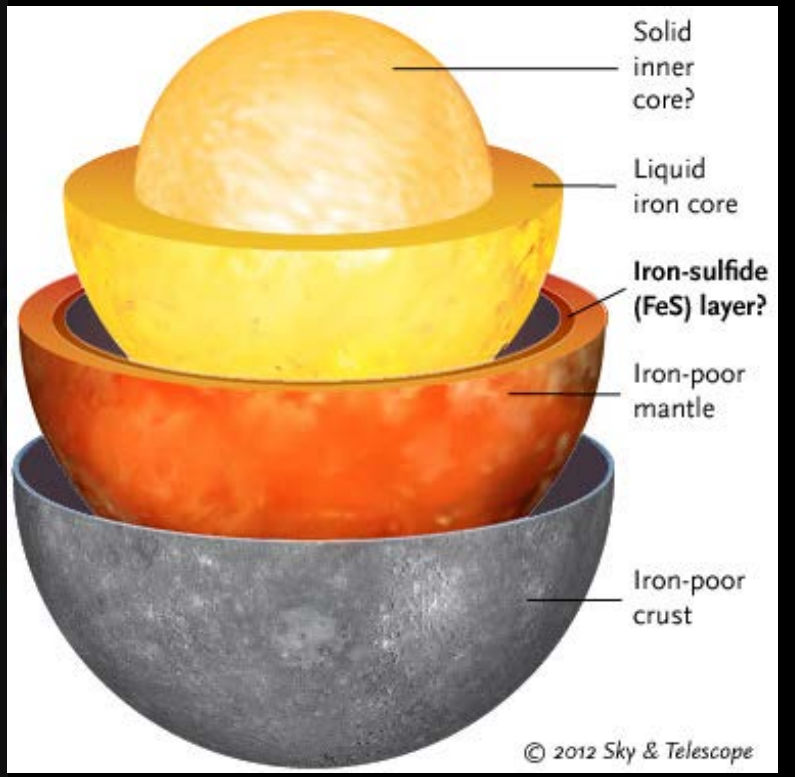




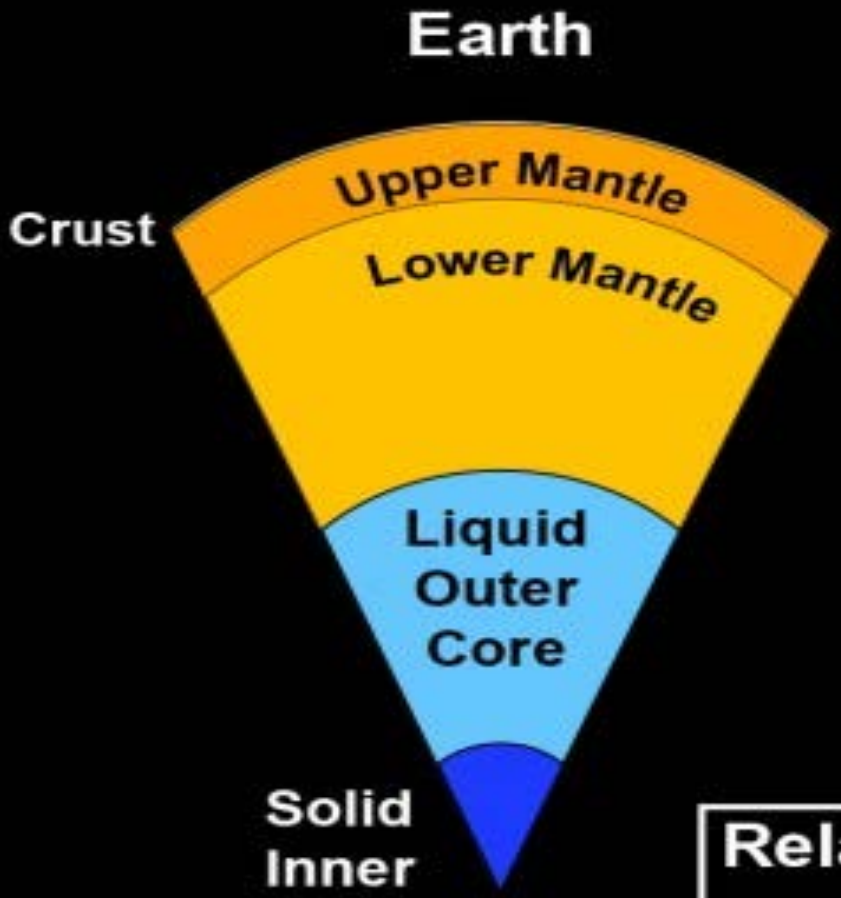


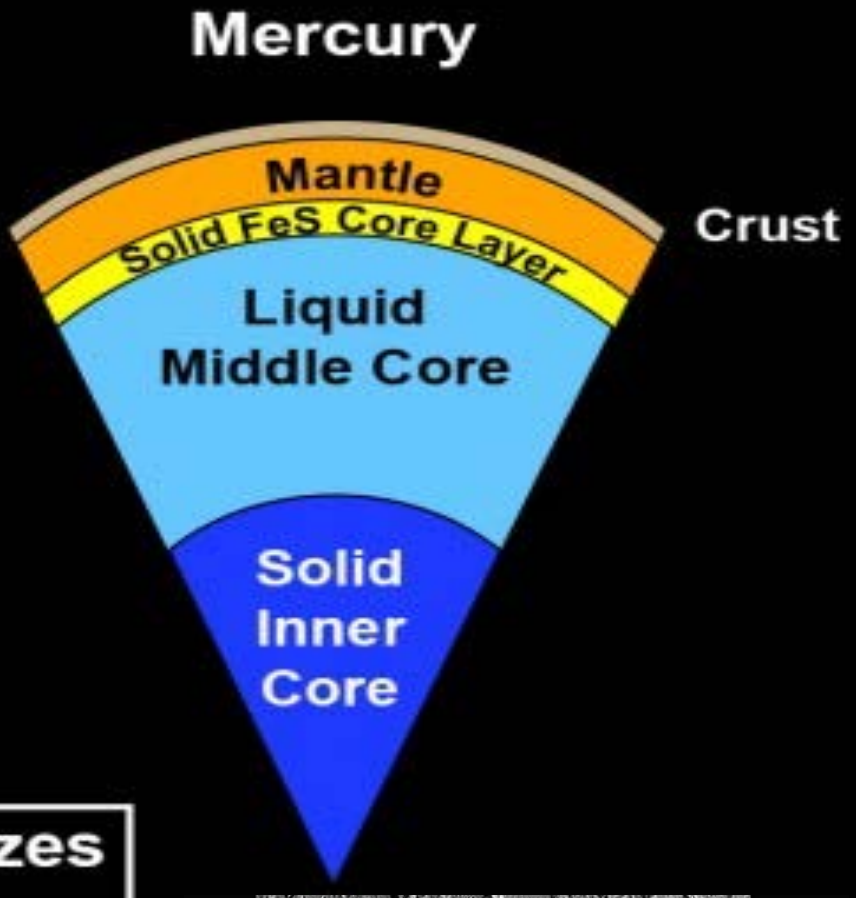
Mercury Mineralogy and Composition

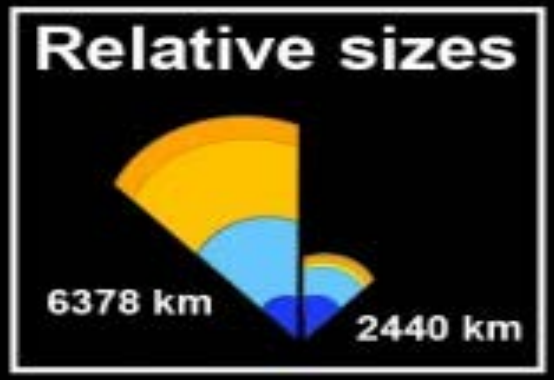


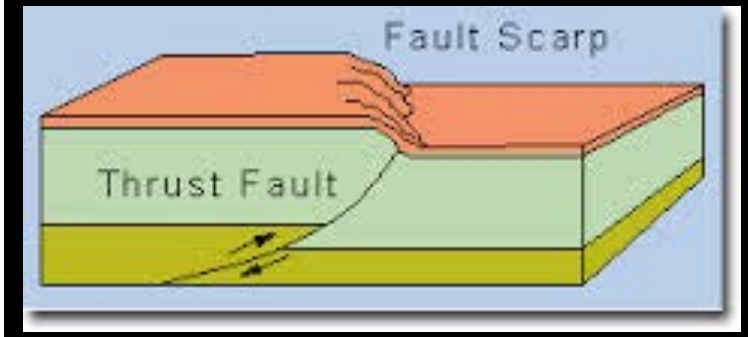


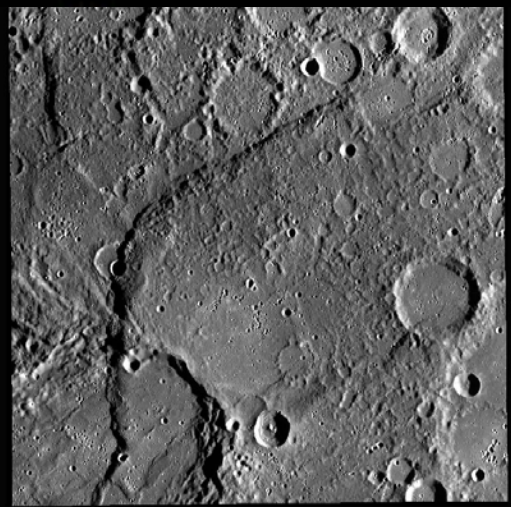
Mercury: Linking Surface Observations to Interior Evolution











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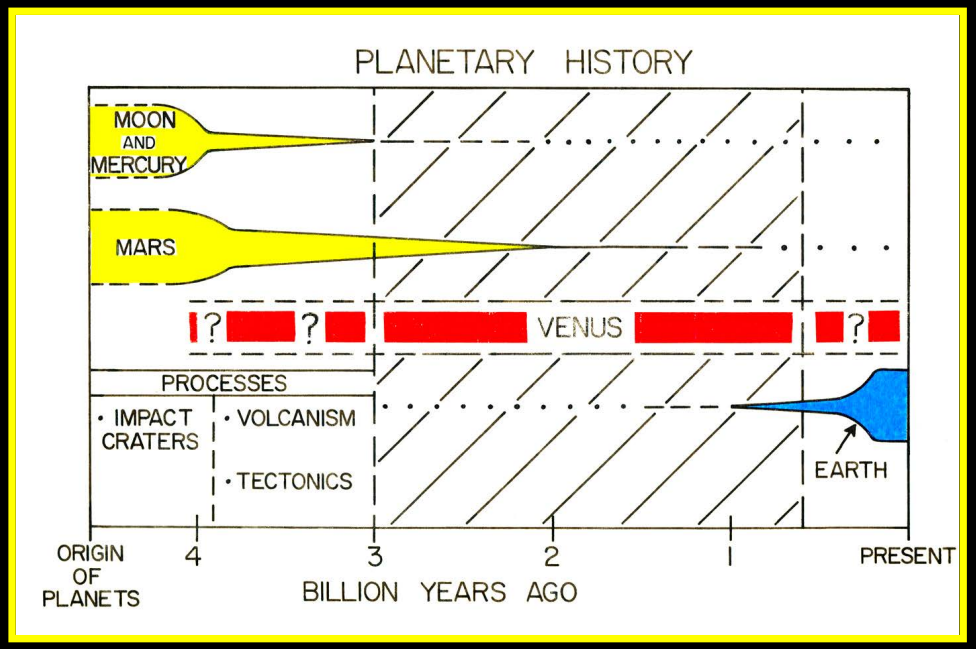
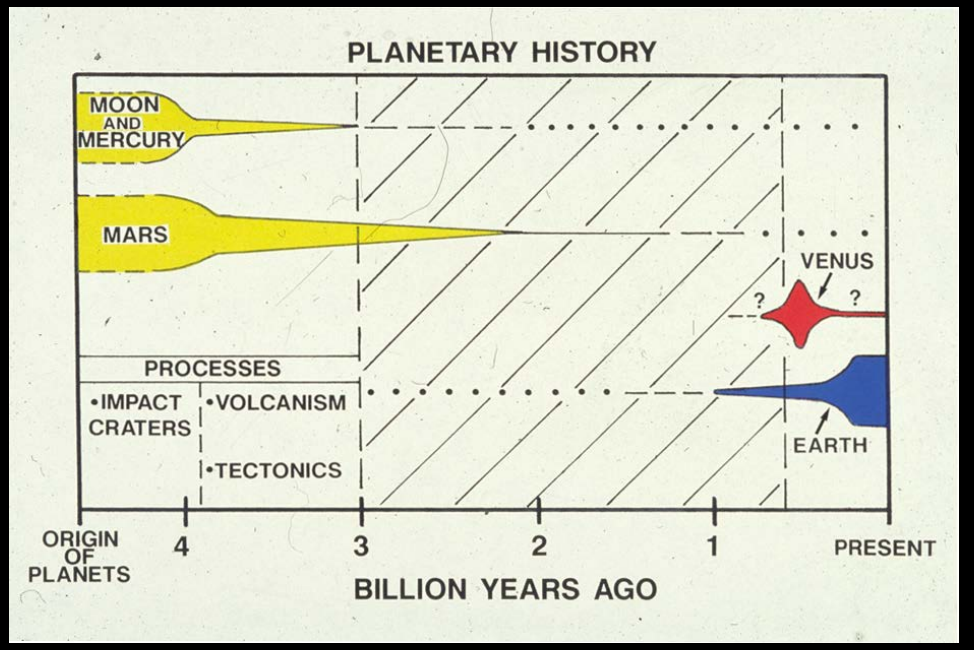
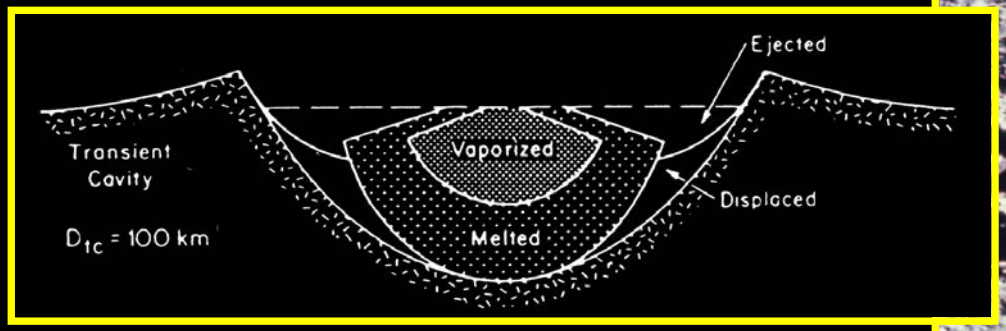
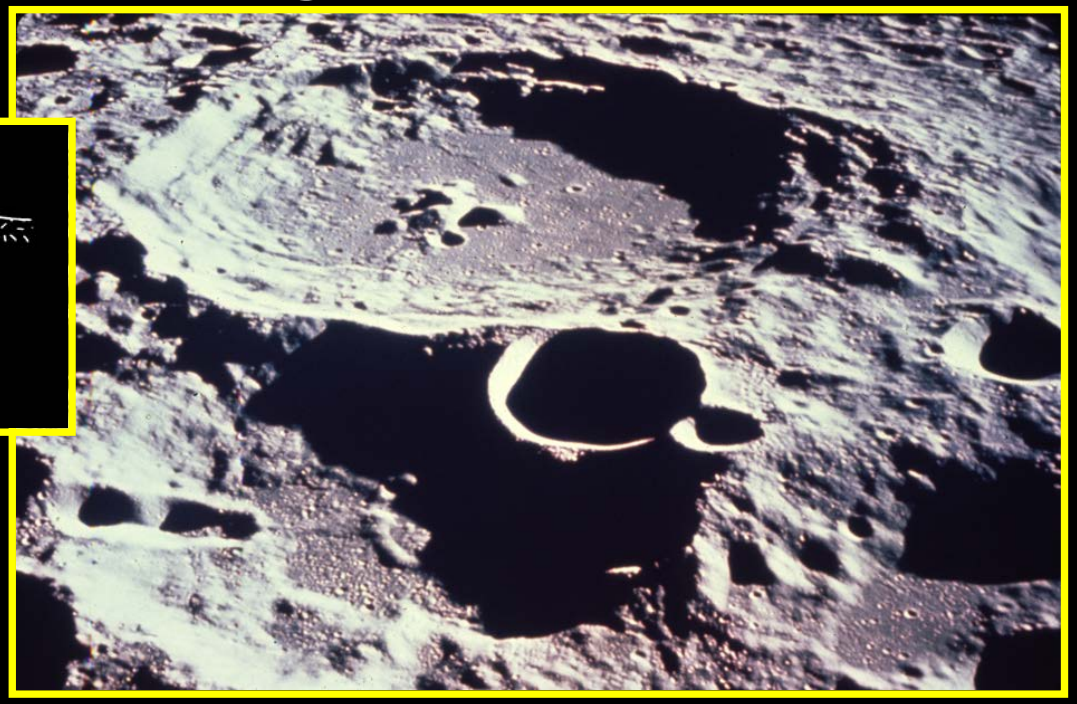




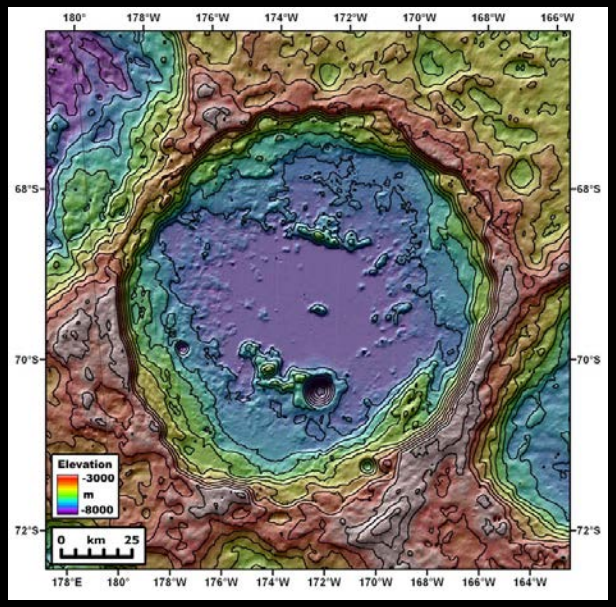
The Moon: A Fundamental Laboratory for the Study of Impact Cratering Processes.

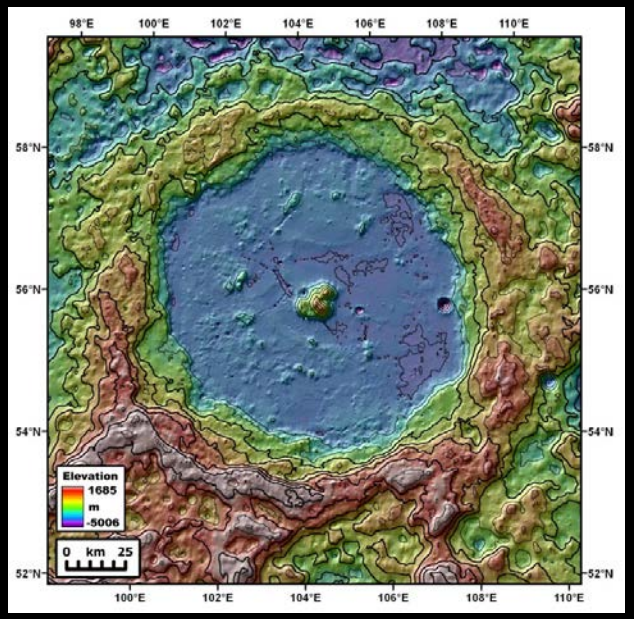


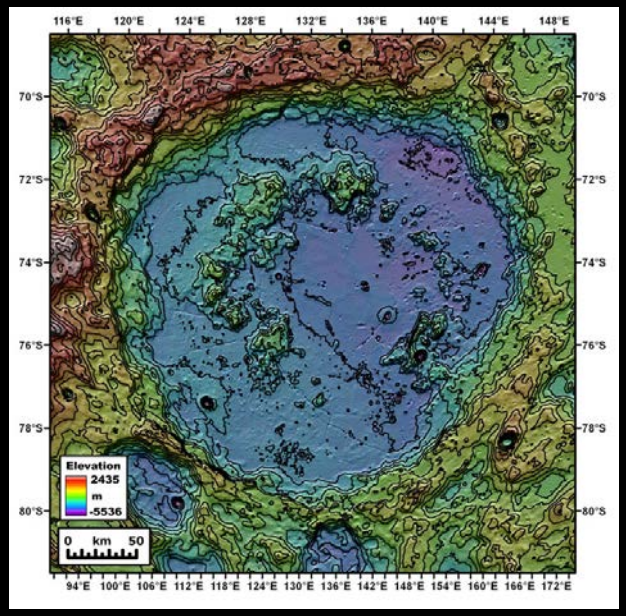


Lunar Reconnaissance Orbiter
Lunar Orbiting Laser Altimeter (LOLA)
LRO Camera (LROC)

(Baker et al., 2010, 2011, 2012)







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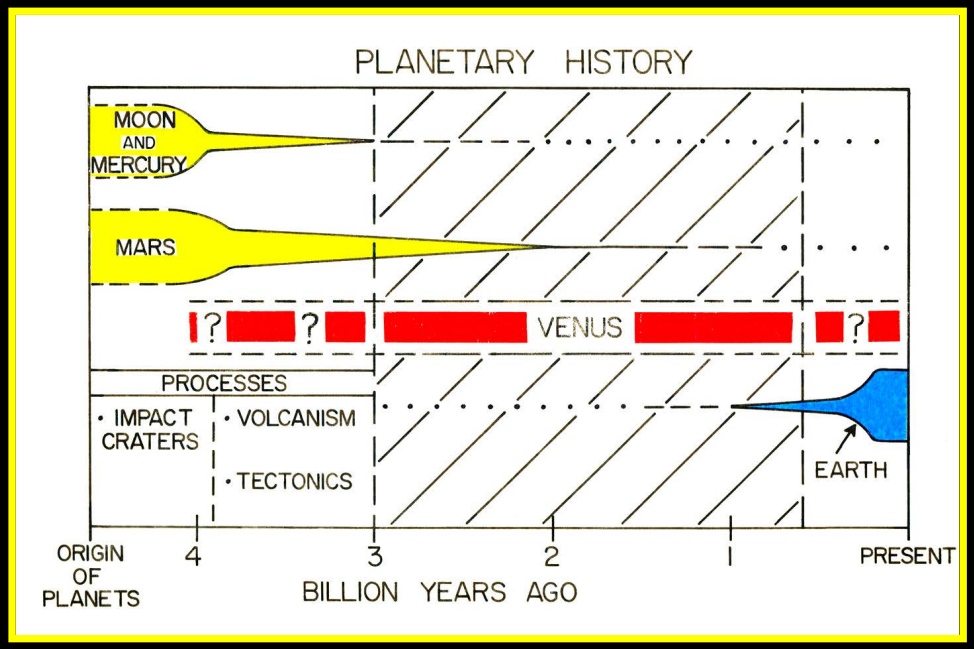
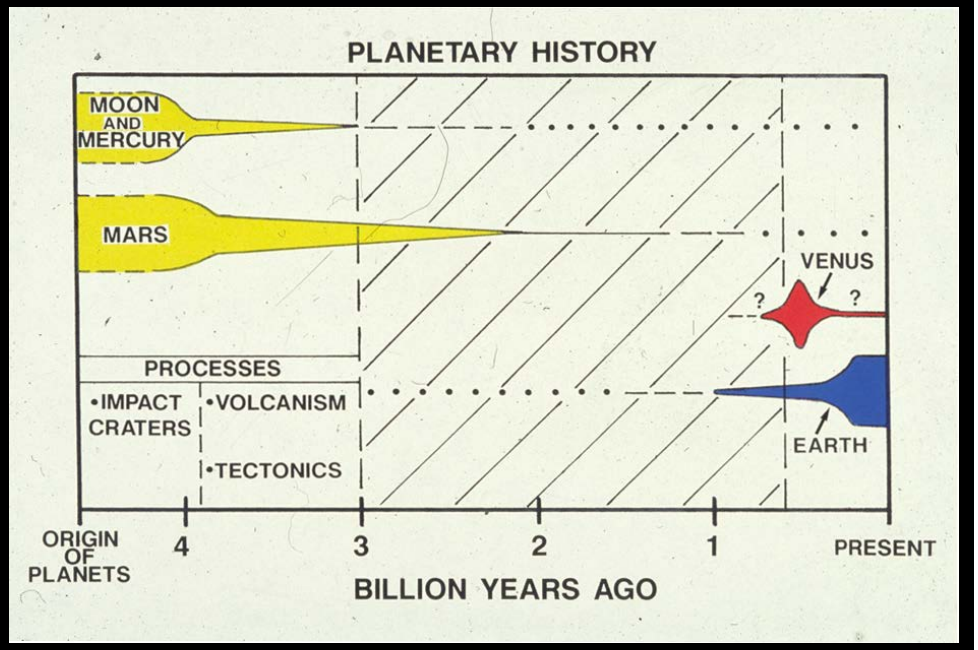
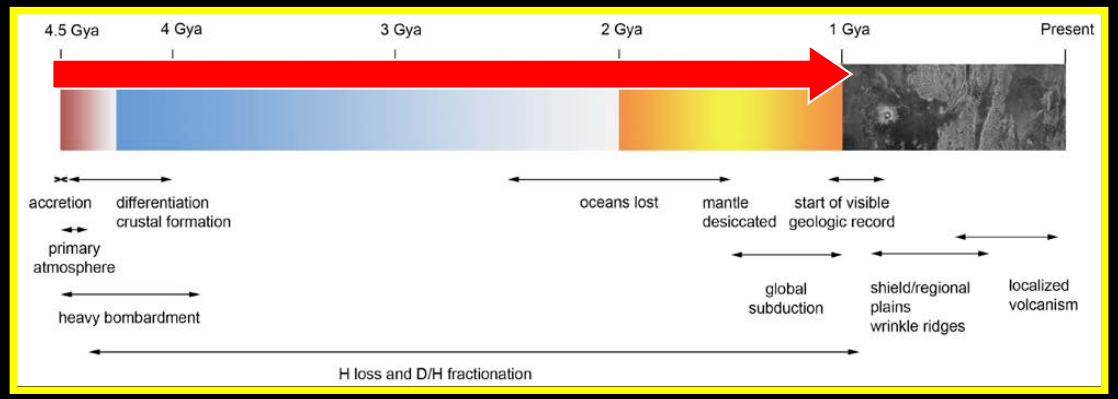




Atmosphere of Venus: Recent or Fossil?

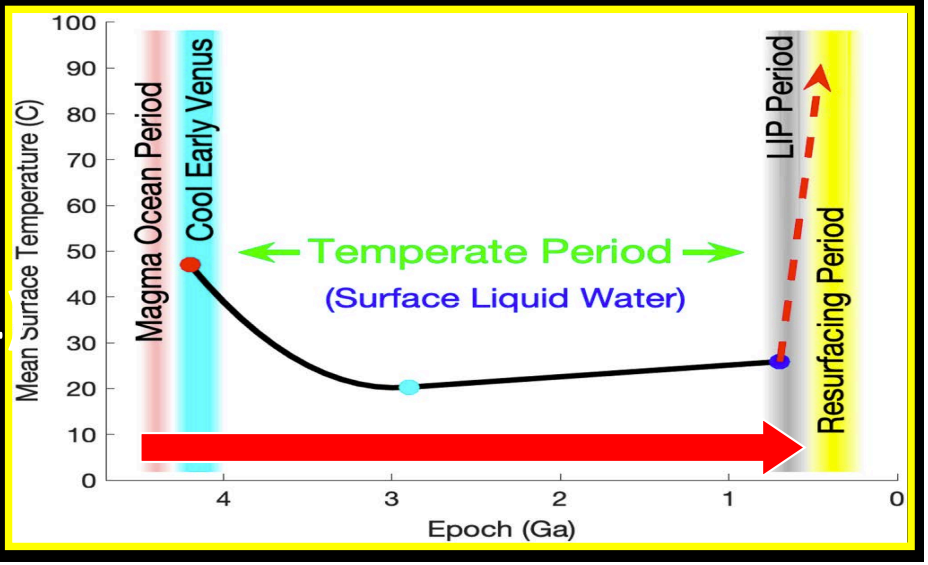
- More Earth-like clement conditions (Bullock & Grinspoon, 1996).



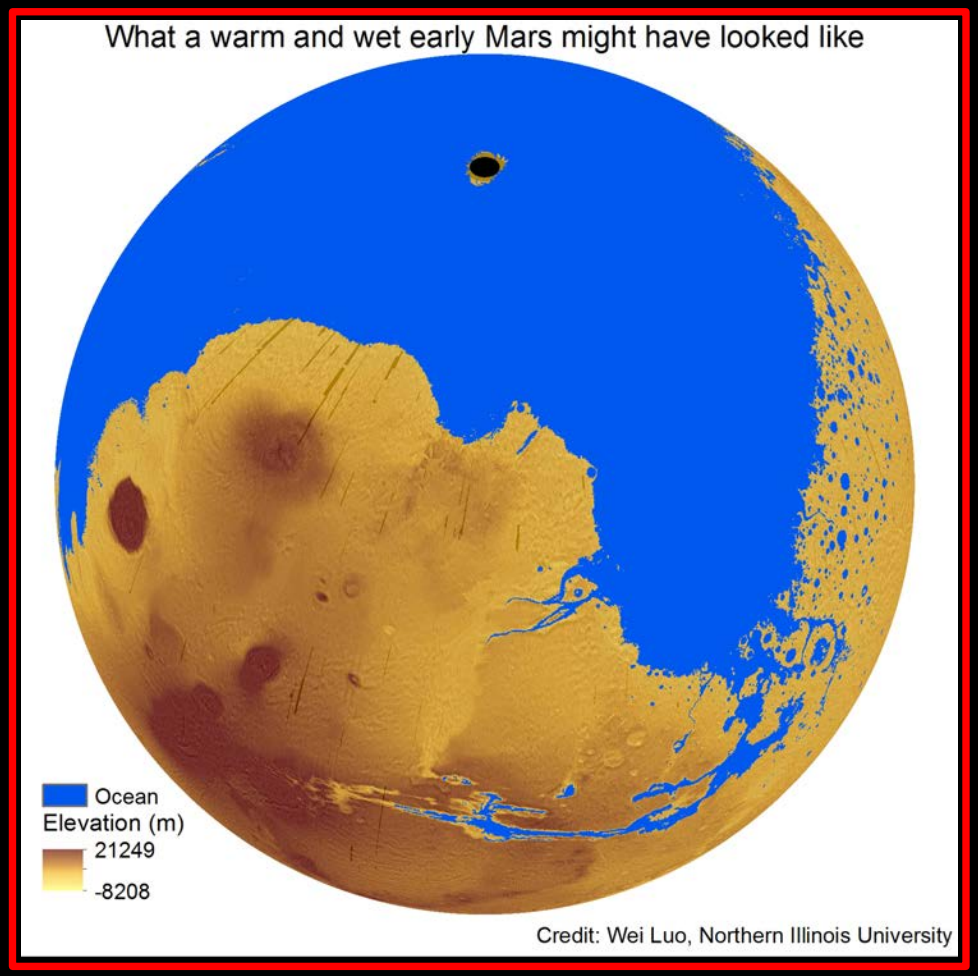
- Oceans and an N_2-dominant atmosphere (Way et al., 2016; Way & Del Genio, 2020).

-These may have carried into the last <20% of Venus' history (post crypto-history; <1Ga).

*BUT, Inverse models (Head et al. 2021 suggest that the current atmosphere is a *fossil* atmosphere?

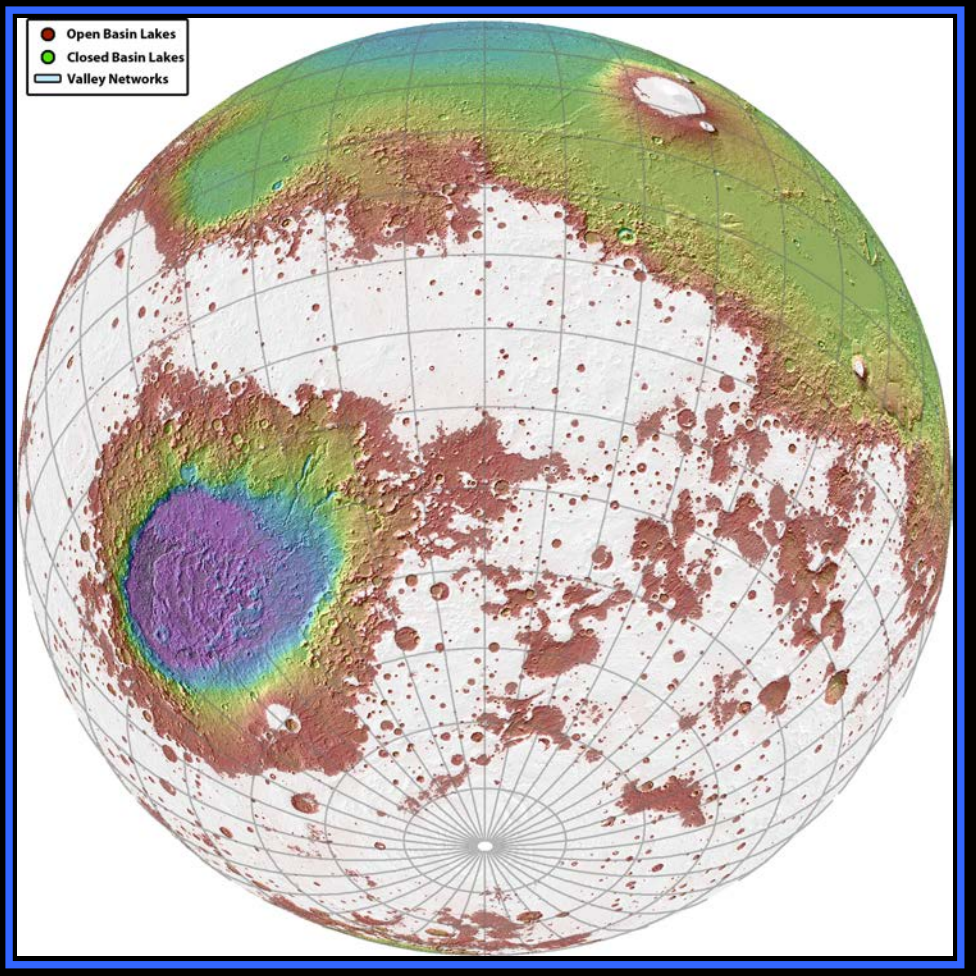


Climate History of Ancient Mars: “Faint Young Sun” Era



“Warm & Wet” Early Mars With Extensive Oceans.

(Luo et al., 2017)

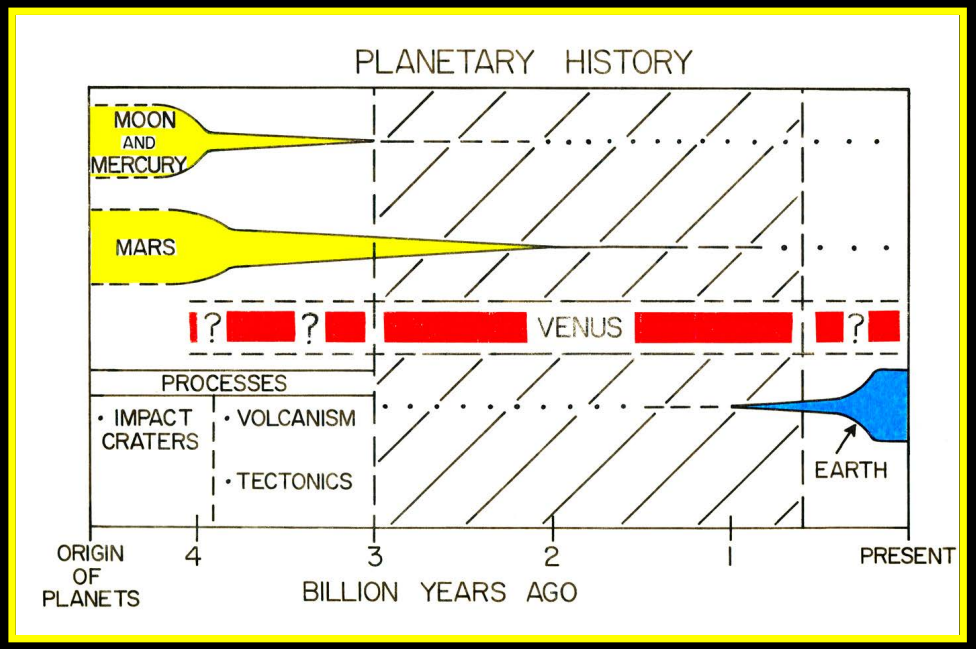


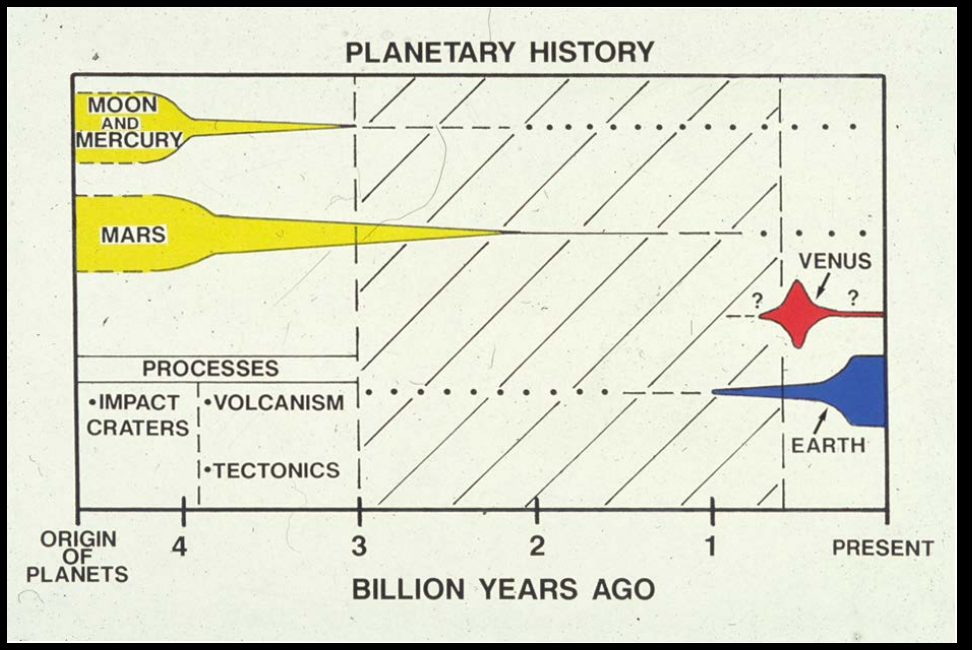
“Cold & Icy” Early Mars With Punctuated Heating and Melting of Ice.

(Wordsworth et al. 2013)
(Head and Marchant, 2015)

Terrestrial Planet Exploration: Findings & Surprises

- 7. Planetary processes:
- 8. Planetary atmospheres:
- **9. Spin-axis/orbital parameters:**
- 10. Geological history:
- 11. Habitability:





Terrestrial Planet Exploration: Findings & Surprises

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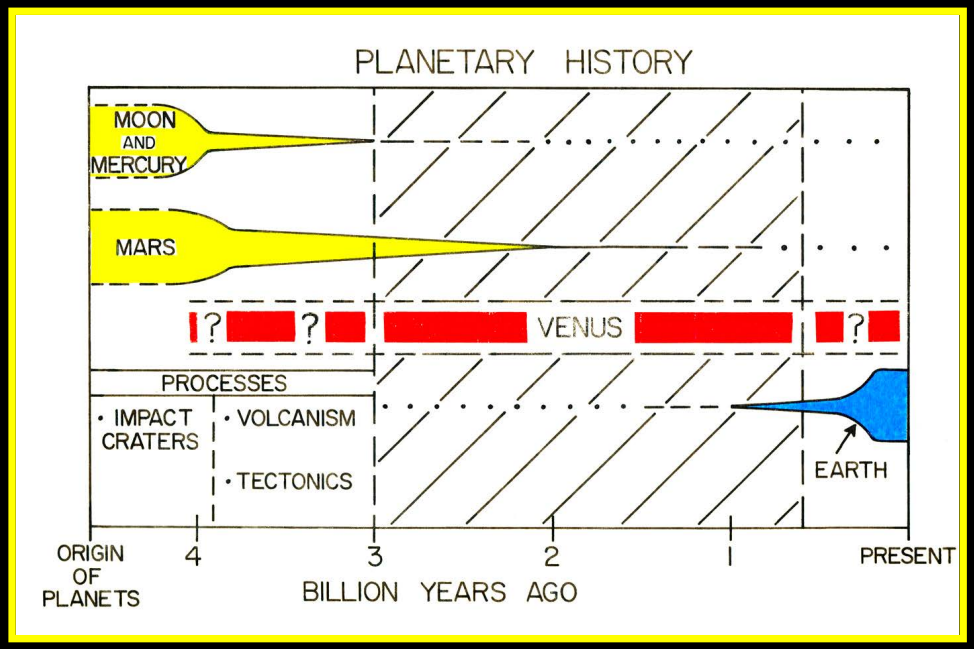
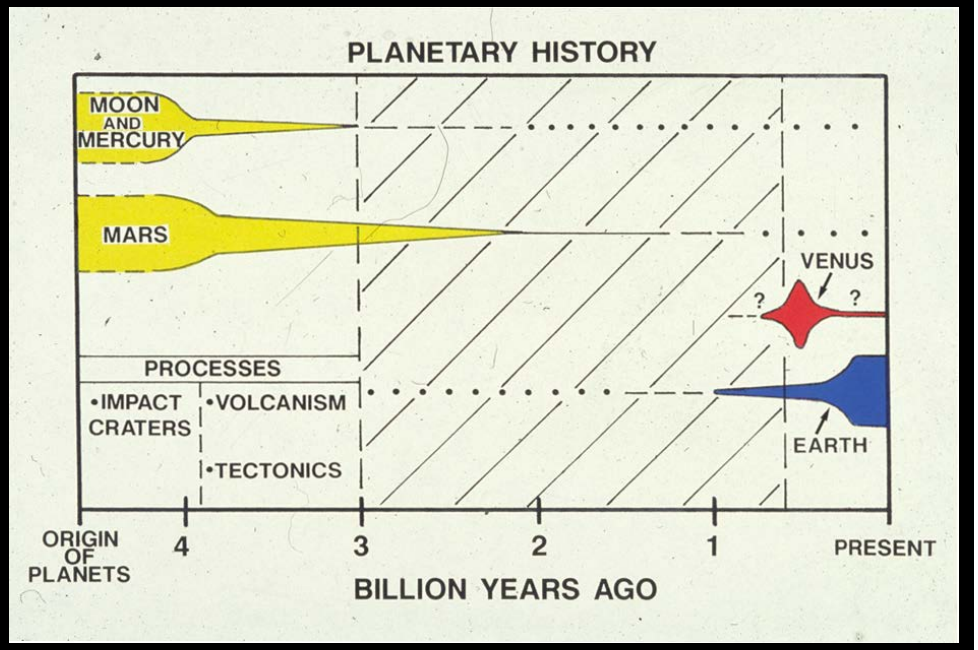
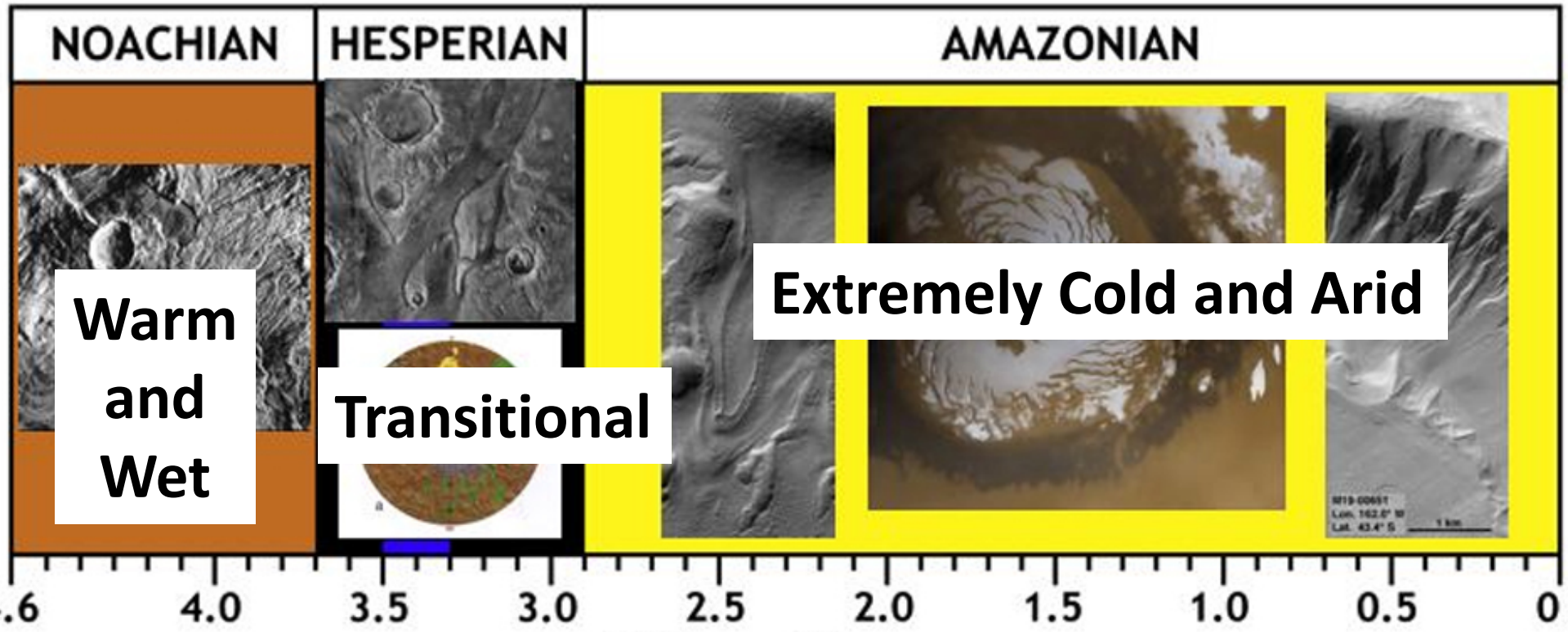




Water and Climate on Mars: Relation to Geologic History/Habitability



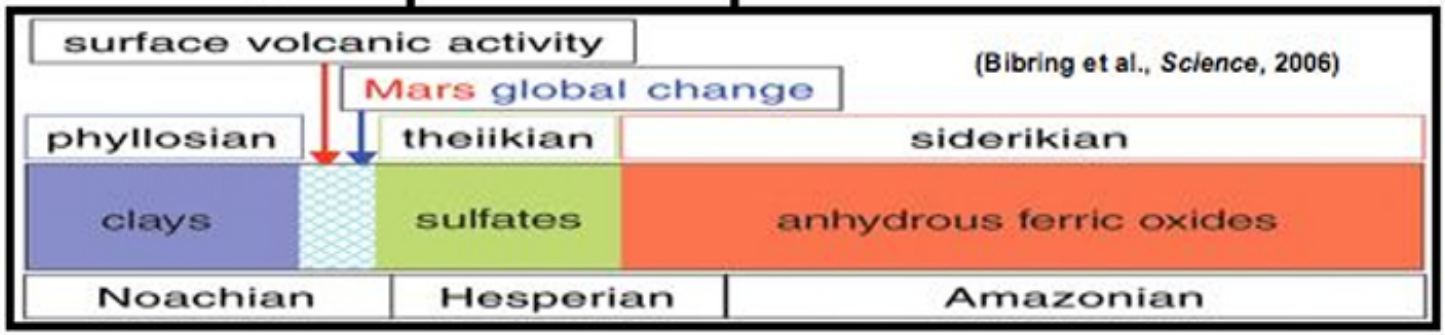
- Heavy impact bombardment, volcanism.
- Valley networks.
- Open-basin lakes.
- "Warm/Wet" early Mars?

- Volcanism.
- Outflow channels.
- Oceans?
- South circumpolar glacial deposits.

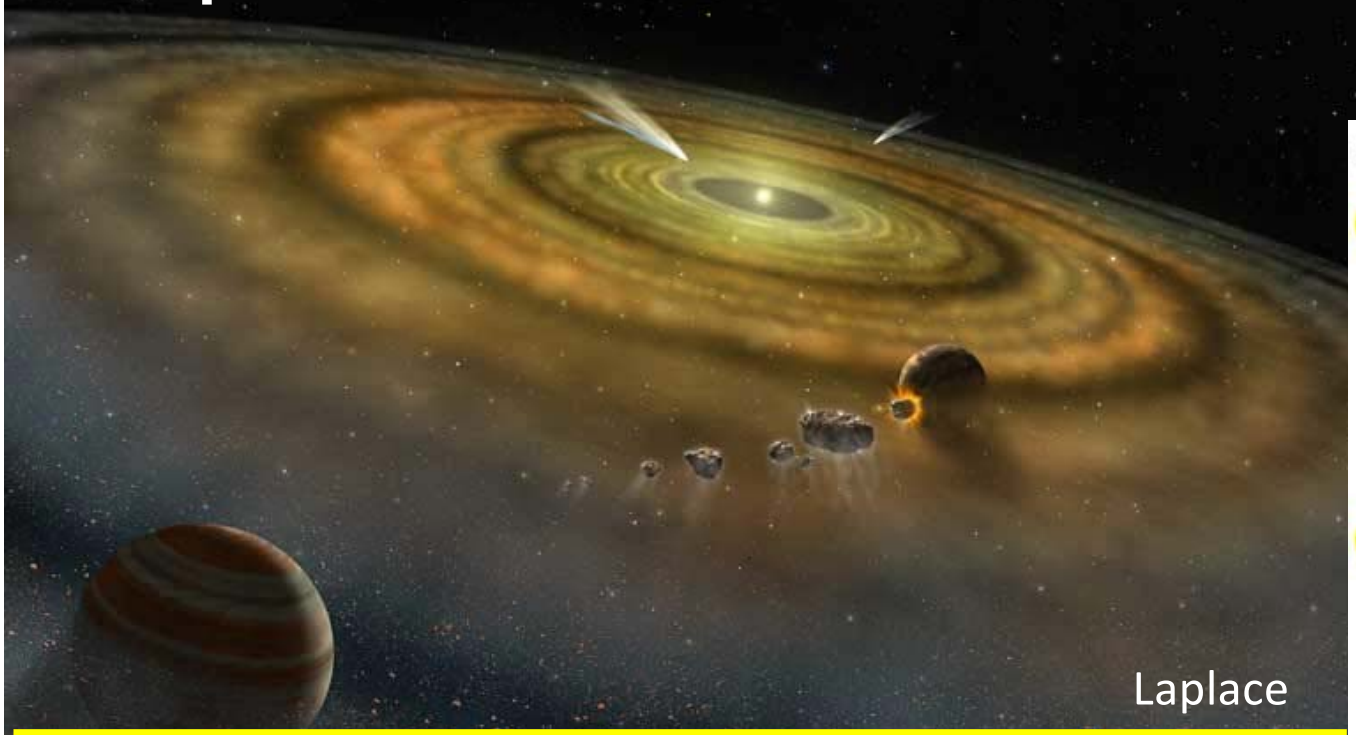
Christensen et al. TES, THEMIS

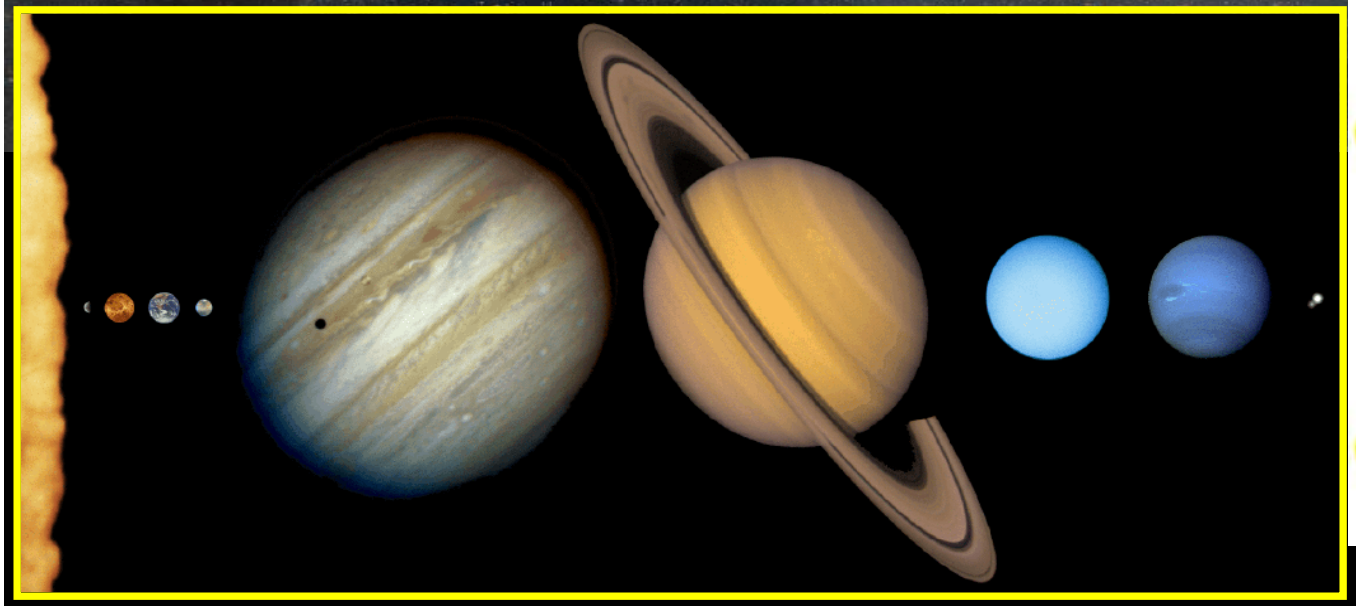
Murchie et al. (2010) Mustard et al. CRISM

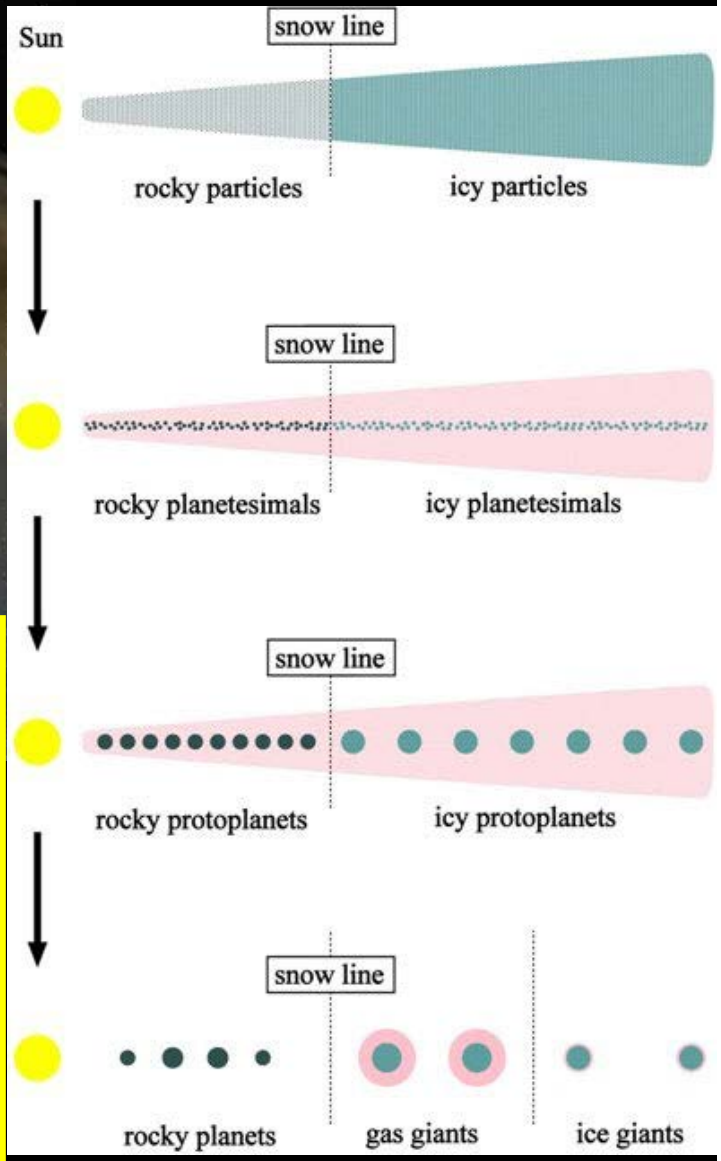
- Low impact rates.
- Tharsis volcanism continues.
- Outflow channels continue at much lower rate.
- Tropical and mid-latitude glaciation.
- Late-stage latitude dependent mid-high latitude layers.
- Late-stage polar caps.
- "Cold/Dry" late Mars.



Collapsing Solar Nebula and Planetary Formation
-Temperature and Pressure as a Distance from the ProtoSun-

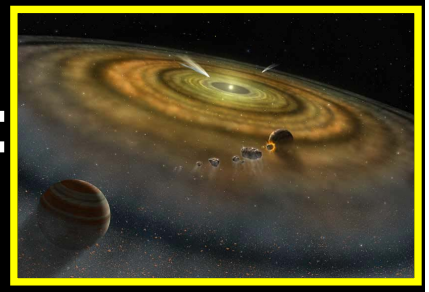


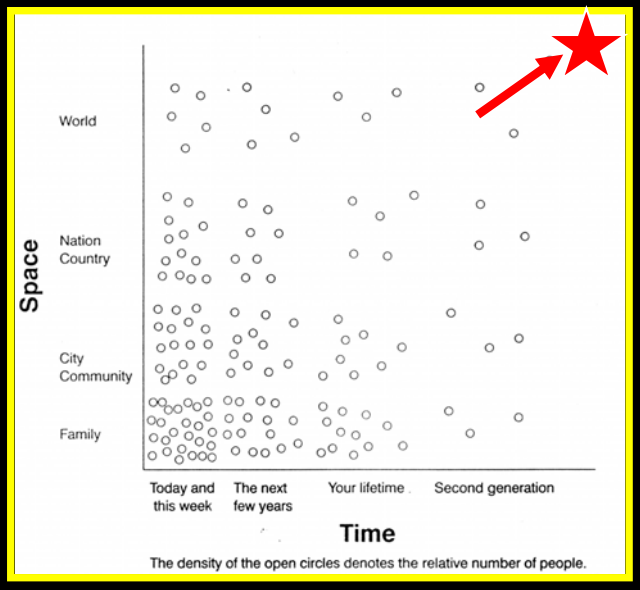


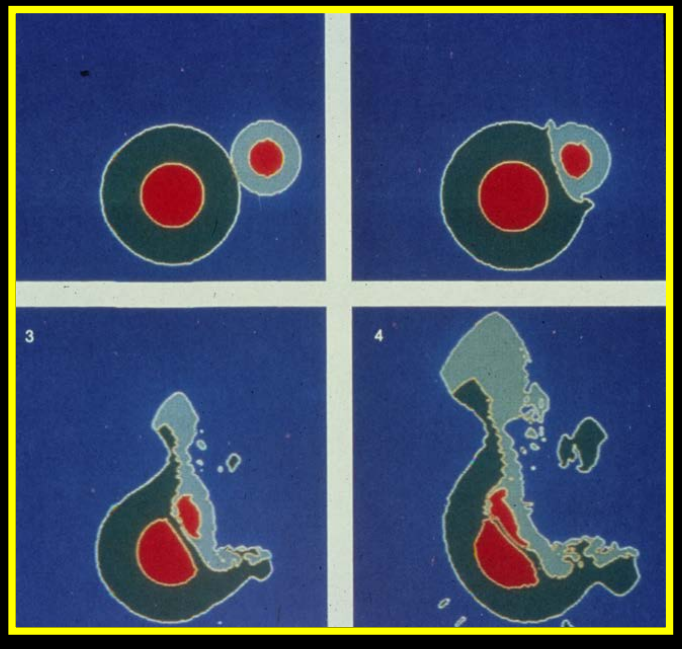


Some Perspectives and Caveats:

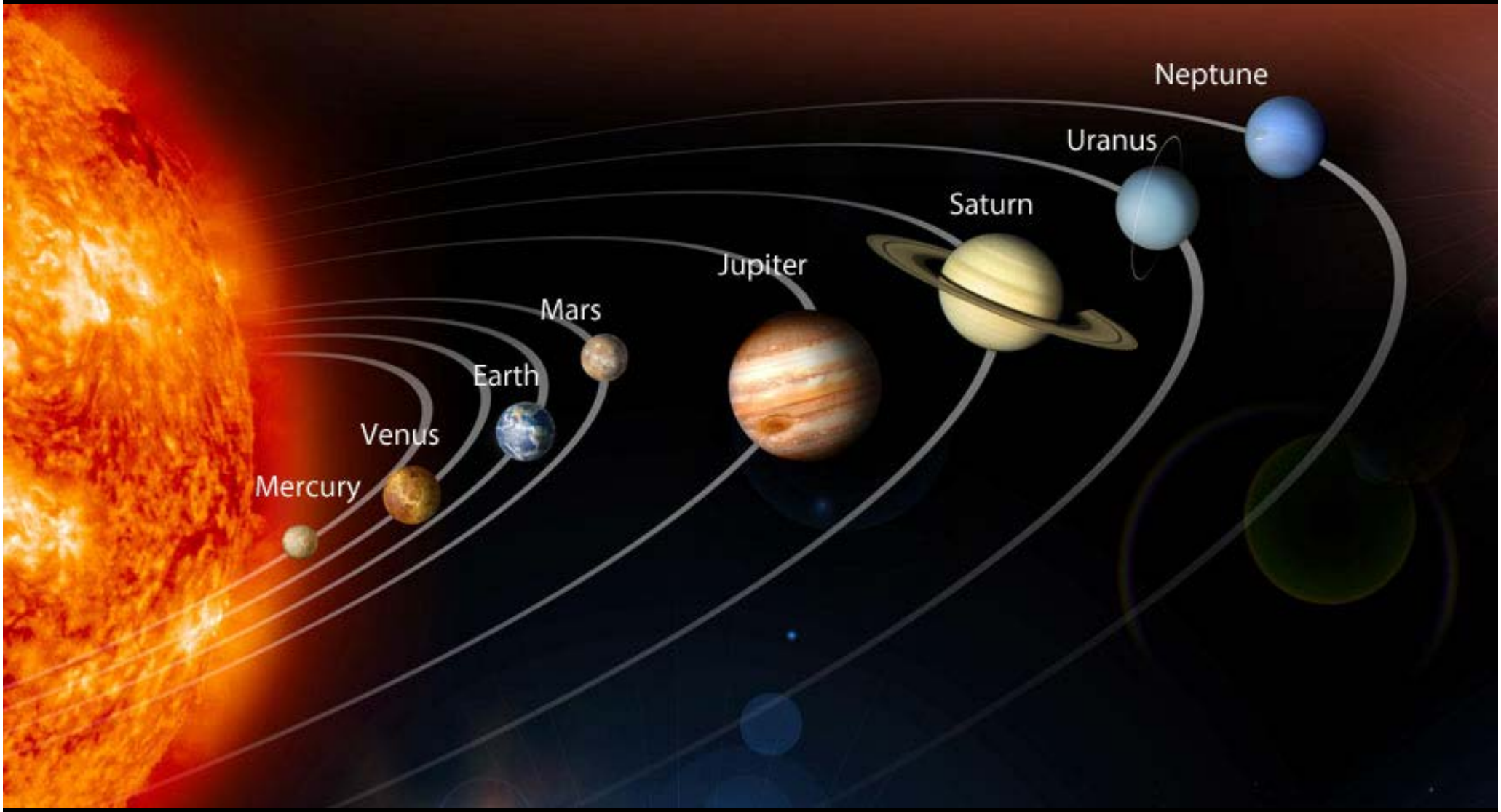
- 1. Terracentrism:
- 2. Uniformitarianism/Catastrophism:
- 3. The Role of Stochastic Processes:
- 4. The Promise and Pitfalls of Paradigms:
- 5. The Space-Time Continuum:
- 6. Don't forget option d): *"None of the above!"*







Era of Solar System Comparative Planetology

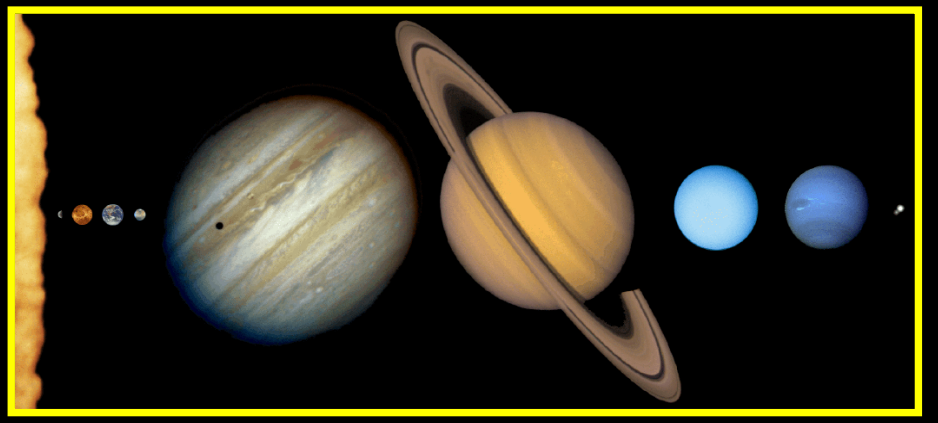


Many fundamental questions remain!!

60+ Years Since Sputnik: The Next 60 Years

Answers to our questions lie in:

1) The results of space missions to be undertaken in the next 60 years of Solar System exploration!

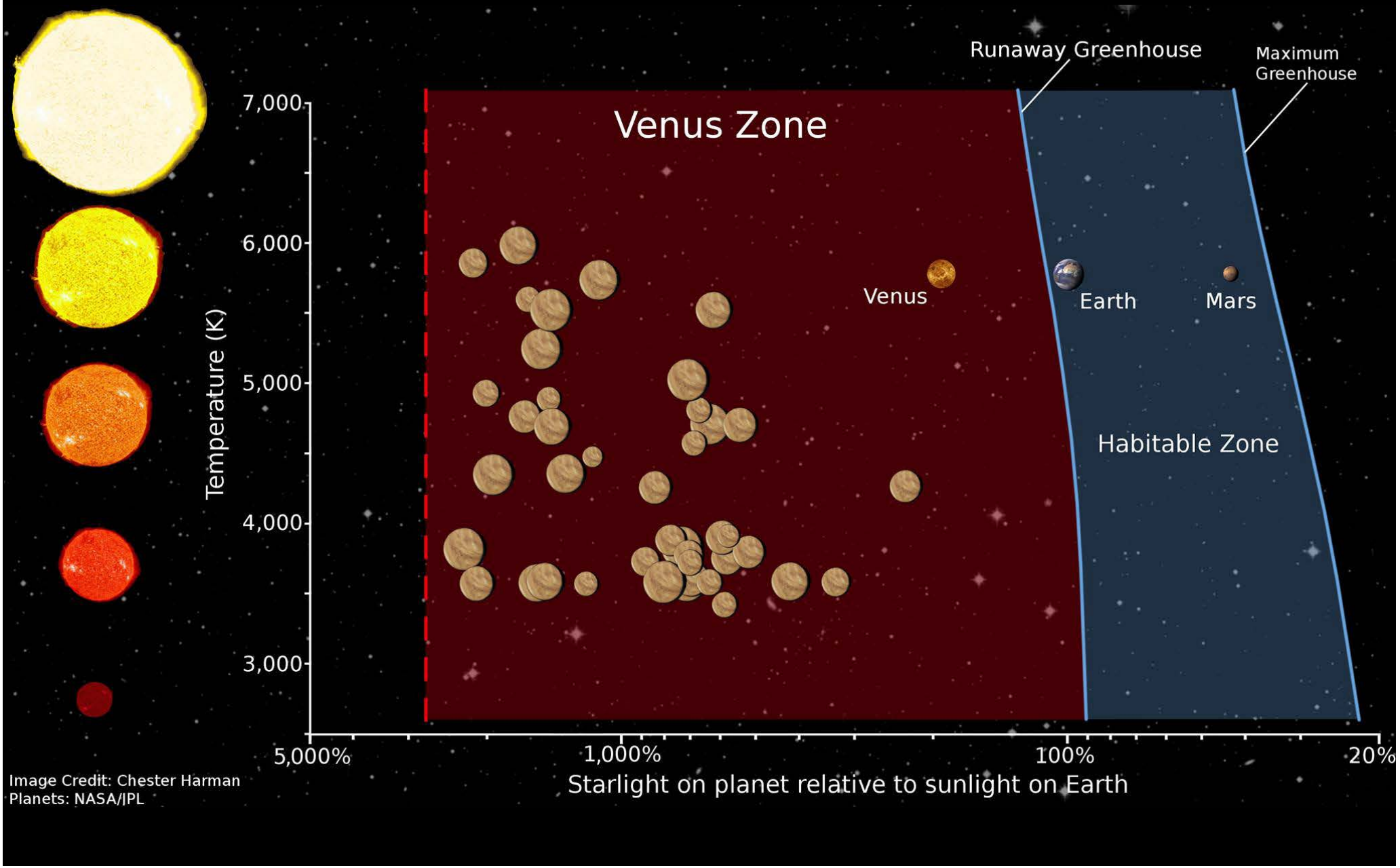


2) The new era of *Comparative Planetary Systems* around other stars.

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



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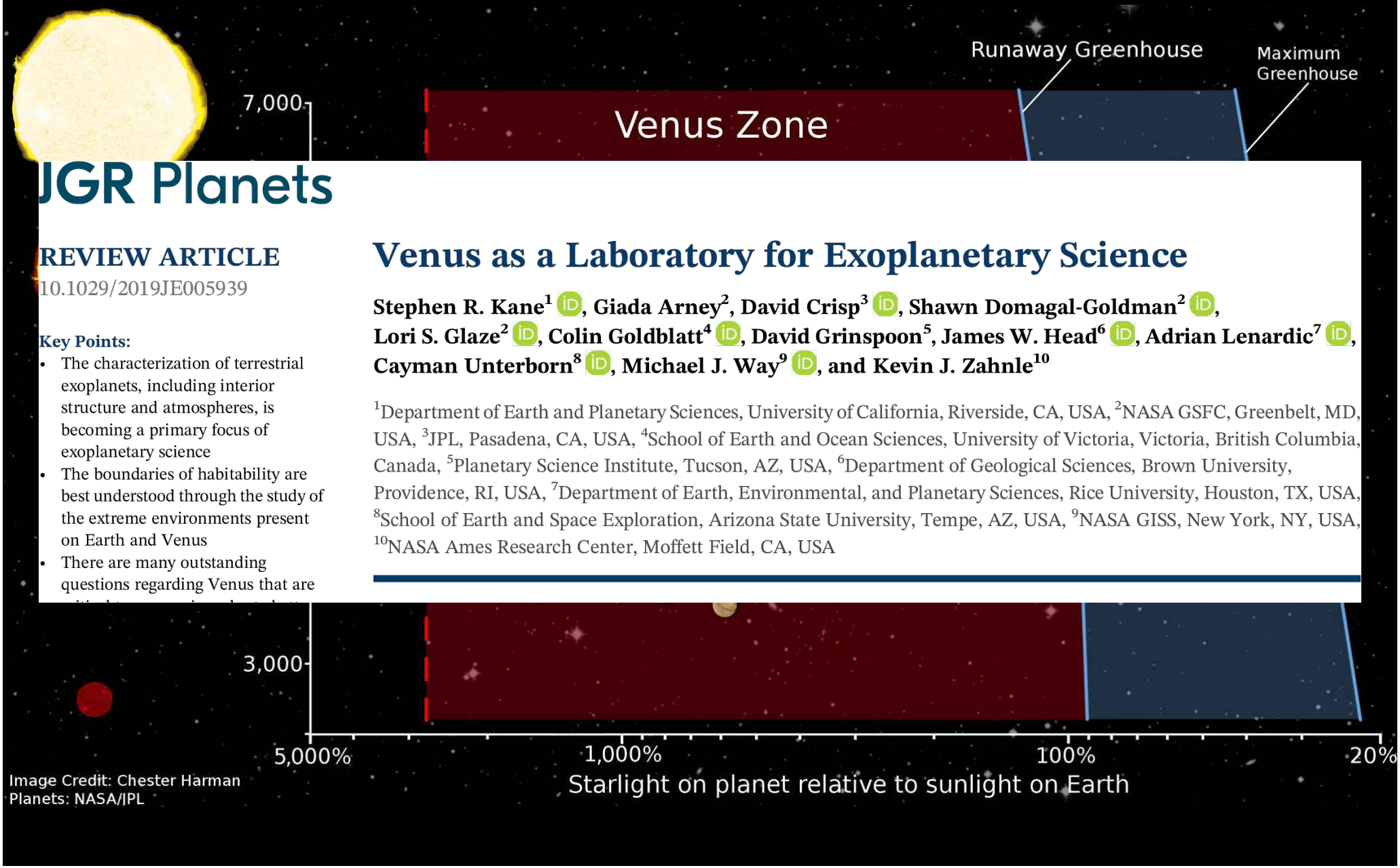


JGR Planets

REVIEW ARTICLE
10.1029/2019JE005939

Key Points:

- The characterization of terrestrial exoplanets, including interior structure and atmospheres, is becoming a primary focus of exoplanetary science
- The boundaries of habitability are best understood through the study of the extreme environments present on Earth and Venus
- There are many outstanding questions regarding Venus that are

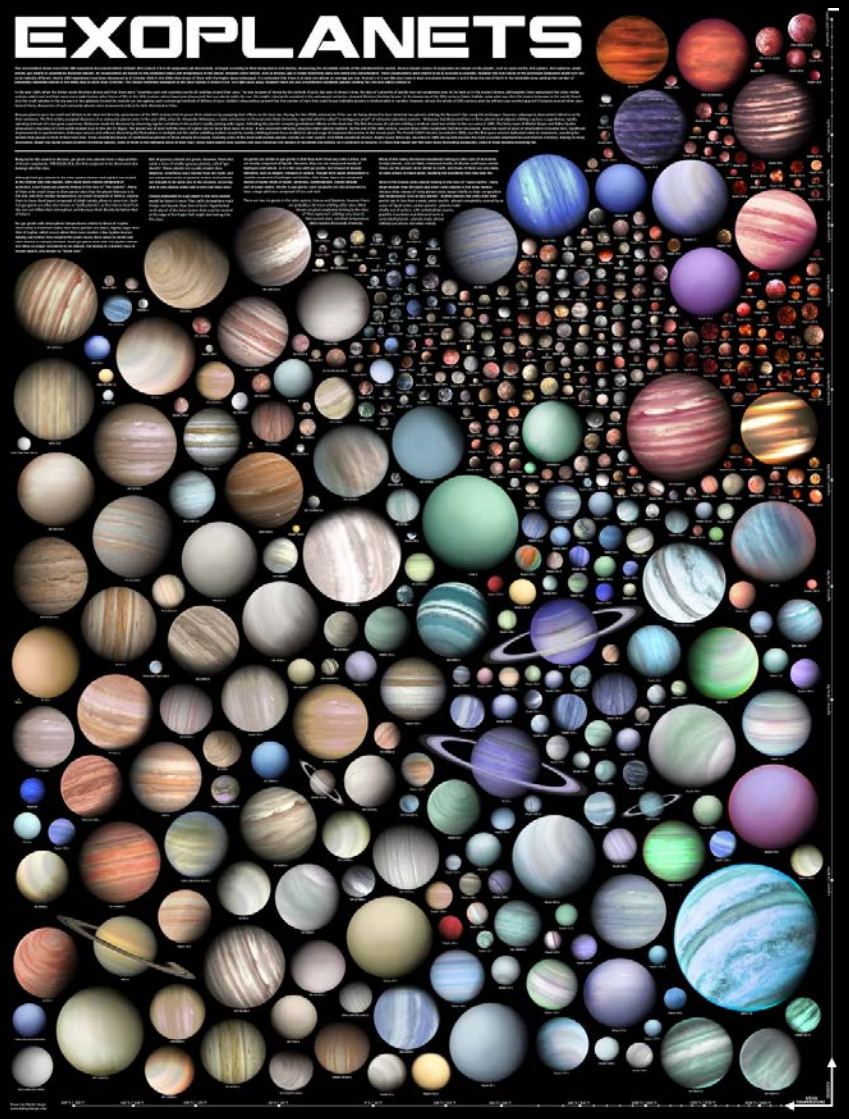
Venus as a Laboratory for Exoplanetary Science

Stephen R. Kane[1], Giada Arney[2], David Crisp[3], Shawn Domagal-Goldman[2], Lori S. Glaze[2], Colin Goldblatt[4], David Grinspoon[5], James W. Head[6], Adrian Lenardic[7], Cayman Unterborn[8], Michael J. Way[9], and Kevin J. Zahnle[10]

[1]Department of Earth and Planetary Sciences, University of California, Riverside, CA, USA, [2]NASA GSFC, Greenbelt, MD, USA, [3]JPL, Pasadena, CA, USA, [4]School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia, Canada, [5]Planetary Science Institute, Tucson, AZ, USA, [6]Department of Geological Sciences, Brown University, Providence, RI, USA, [7]Department of Earth, Environmental, and Planetary Sciences, Rice University, Houston, TX, USA, [8]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA, [9]NASA GISS, New York, NY, USA, [10]NASA Ames Research Center, Moffett Field, CA, USA

The Era of Comparative Planetary Systems!
An Era of Collaboration Between Astronomers and Planetary Geoscientists!

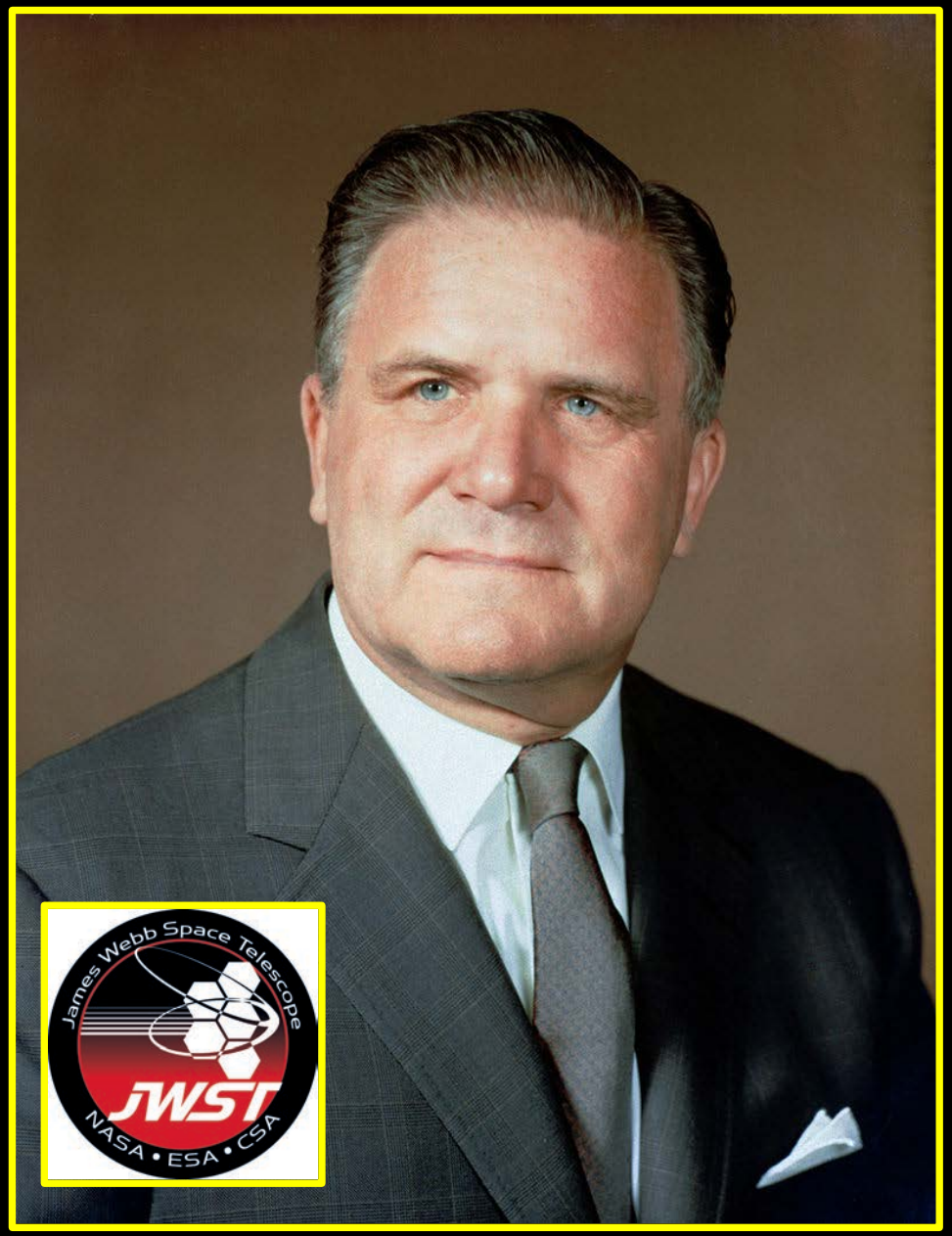
The Solar System

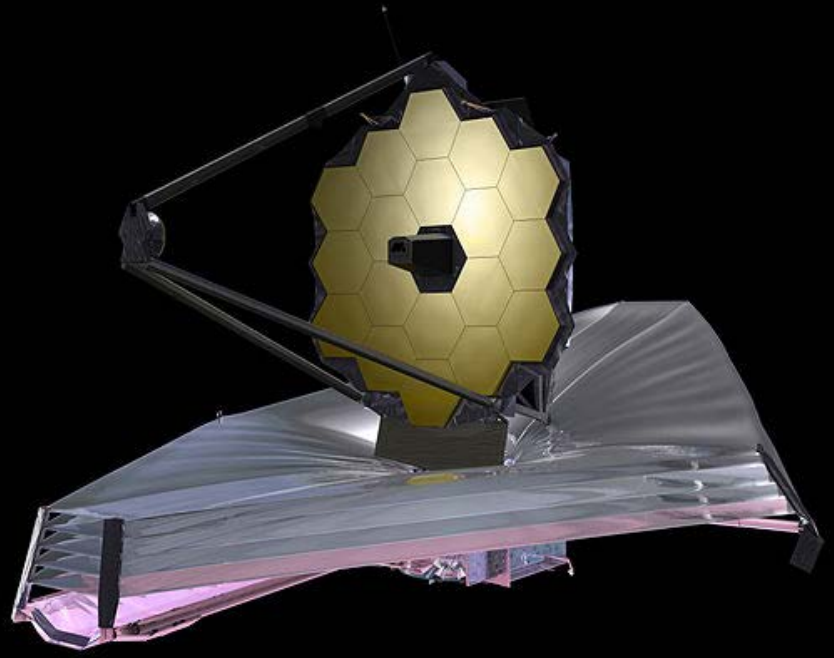


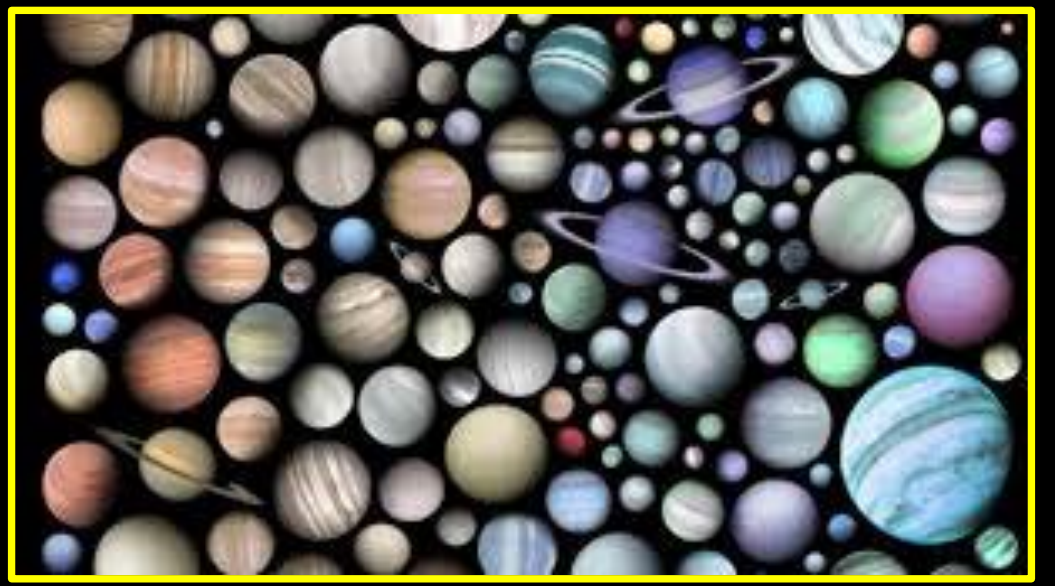
Einstein: “Everything has changed but our way of thinking!”

8/1/21 4801

James E. Webb – NASA Administrator







The Era of Comparative Planetary Systems!

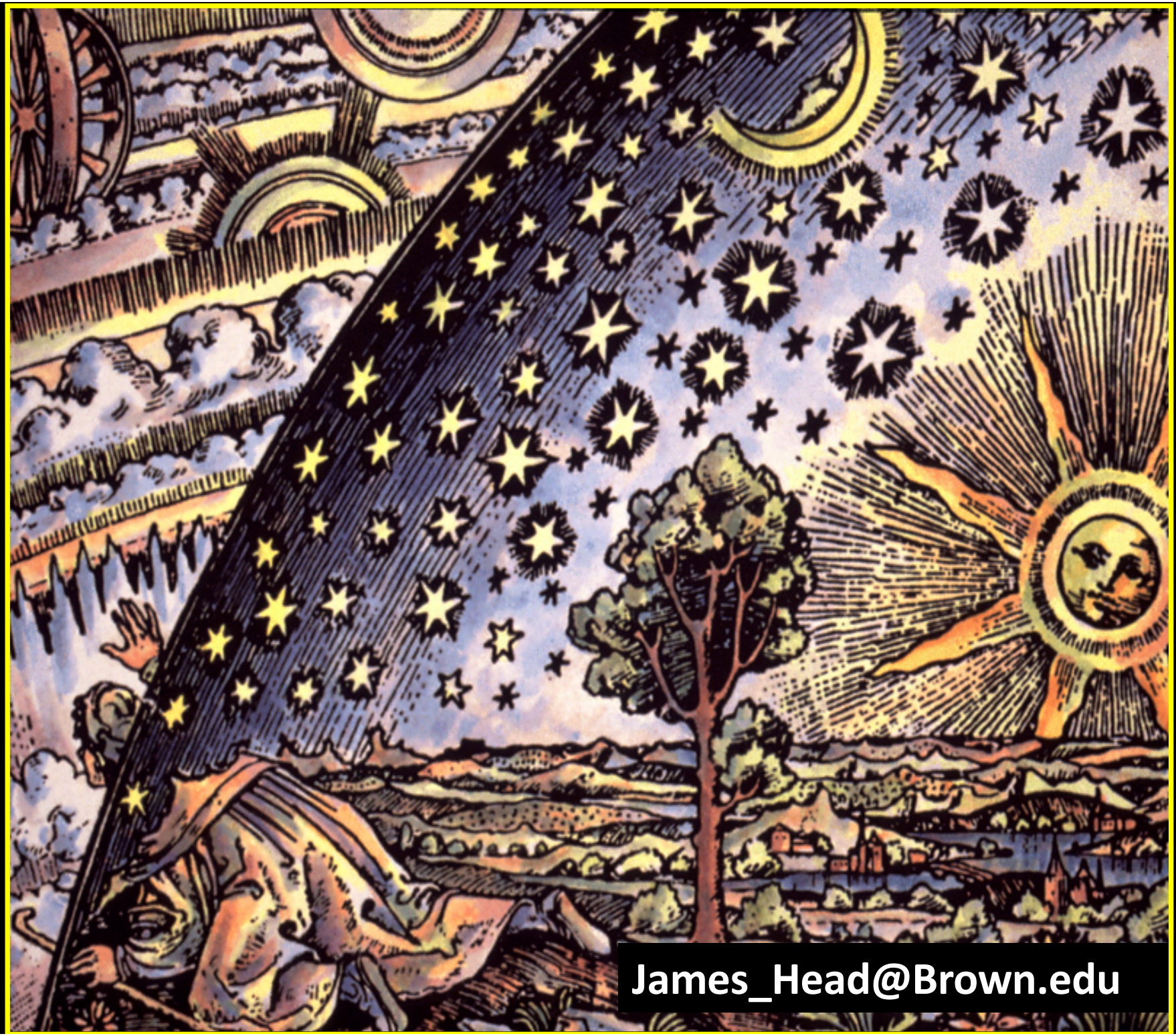
Let’s Play Marbles Together!!

Solar System Community Opportunities:

- Other planetary systems offer **untold numbers of individual examples of planets, systems of planets, and stars.**
- Exploration of this **huge parameter space is yet another framework** for increased understanding of the origin and evolution of our Solar System.
- The ***Exoplanet Perspective*** can also assist in the development of **future Solar System exploration strategies.**

Exoplanet Community Opportunities :

- The ***Solar System Perspective*** provides a **rich and accessible record of the origin, evolution and fate of a small number of planets and satellites.**
- The **lessons learned** from initial assumptions and evolving outcomes is both instructive and sobering, and **provides a template for exploring and understanding other planets and planetary systems.**



James_Head@Brown.edu