Comparative Planetary Environments

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Heliophysics Summer School 2024

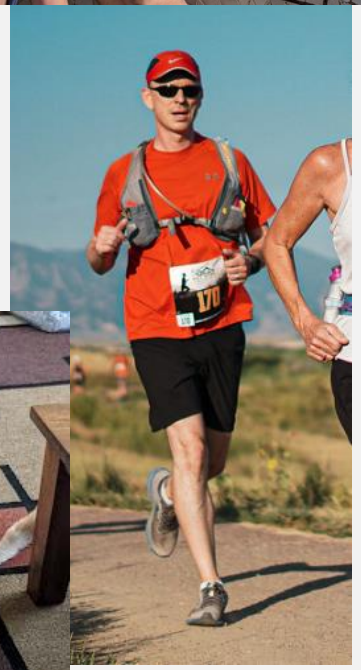
19 Aug 2024

You are encouraged to be interactive

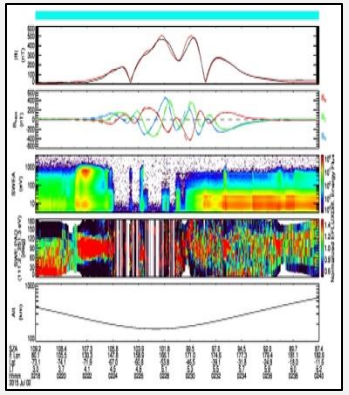
Introductions

- Name
- Pronouns
- Home institution
- Your heliophysics sub-discipline in 2-3 words (e.g. “Earth magnetosphere”)
- Favorite planet

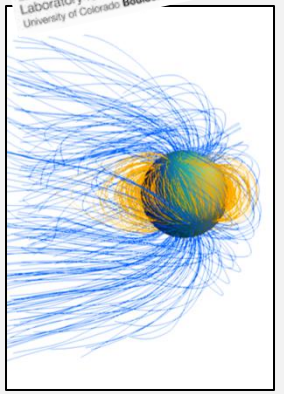
Dave Brain

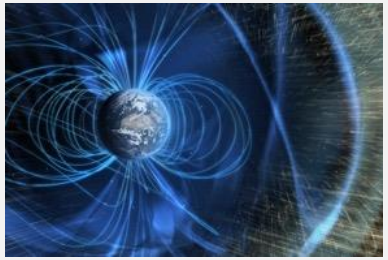


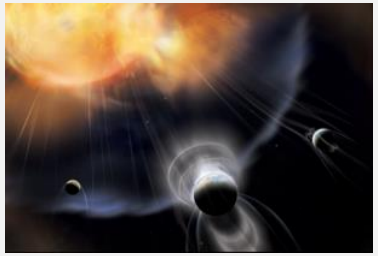
Astrophysical & Planetary Sciences
COLLEGE OF ARTS & SCIENCES



LASP
Laboratory for Atmospheric and Space Physics
University of Colorado Boulder

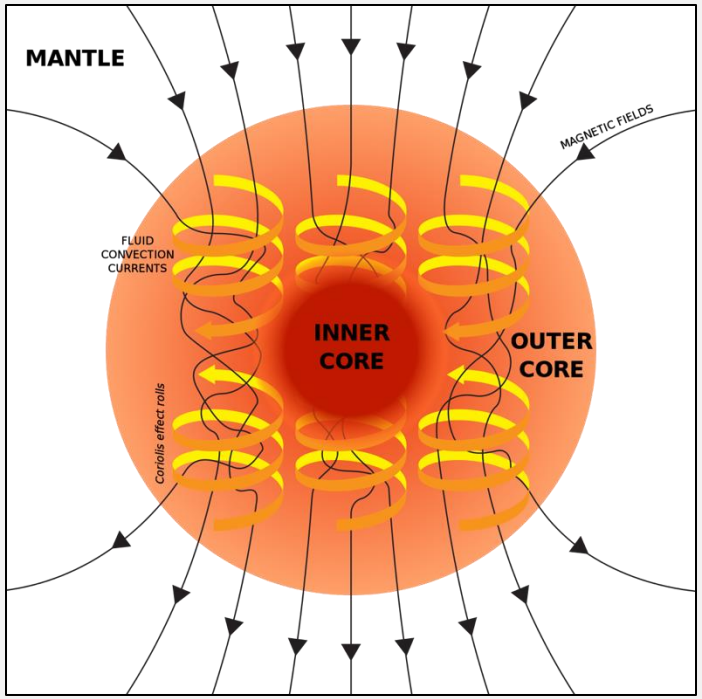






1. Comparative Solar System Magnetospheres

Intrinsic Magnetospheres



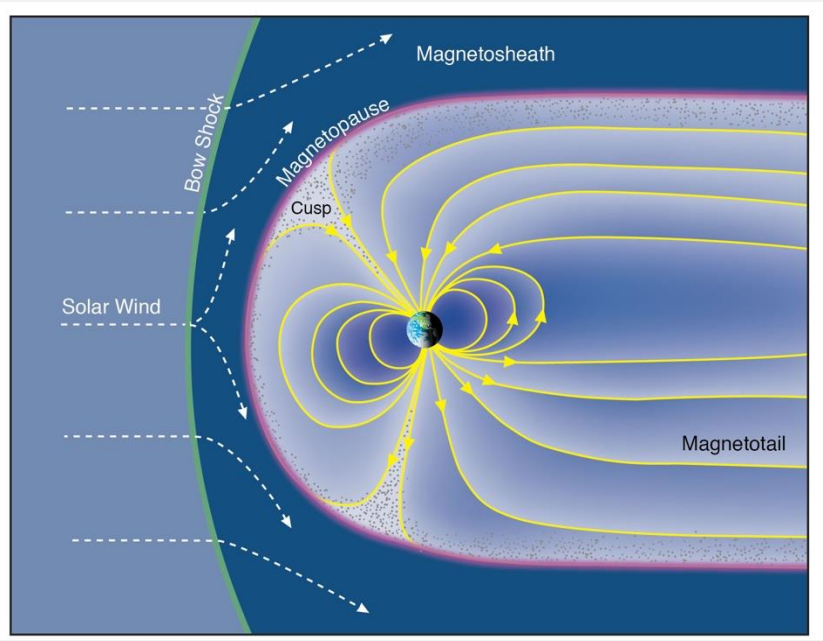
Some planetary bodies generate global magnetic fields in their interior

- Require electrically conducting fluid, convection, rotation

The magnetic field provides sufficient pressure to divert incident plasma around the planet

$$\rho_{SW}\, v_{SW}^2 = \frac{B^2}{2\mu_0}$$

Pressure of flowing solar wind Pressure of planet's magnetic field



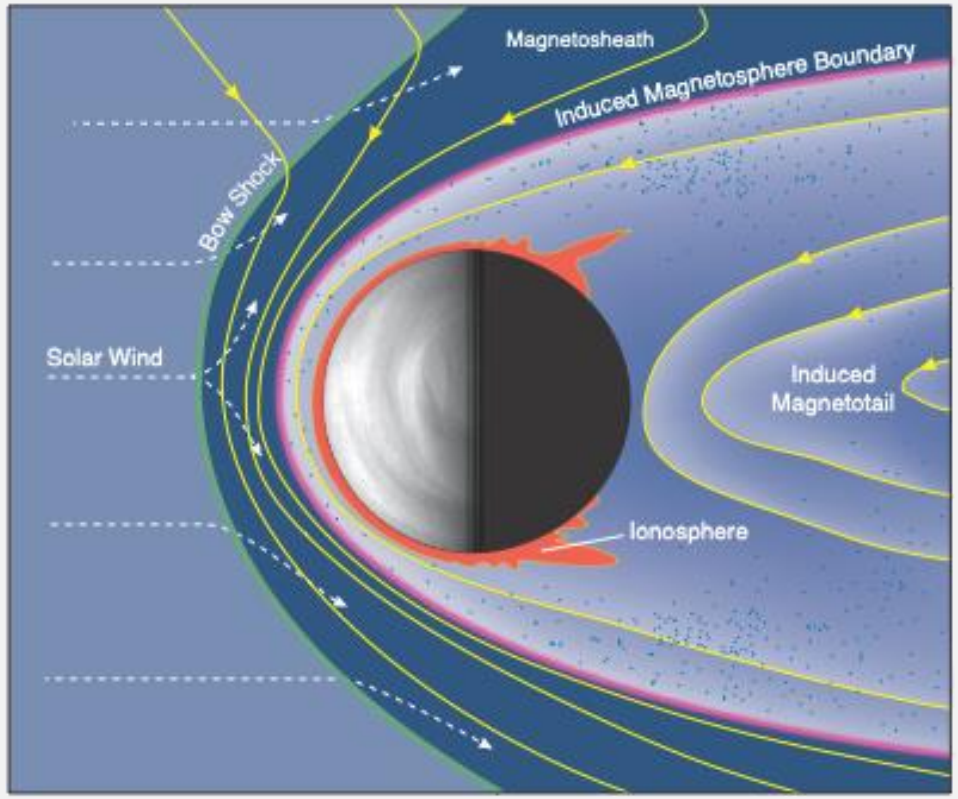
Induced Magnetospheres

Some planetary bodies have magnetic fields induced by their interaction with the space environment

- Magnetic field sufficient to deflect incident plasma

Induction mechanism

- Incident plasma carries a magnetic field
- Faraday's Law: changing incident B-field induces a current in planetary charge carriers (ionosphere, salty ocean)
- Ampere's Law: the induced current creates a magnetic field that deflects incident plasma



Pop Quiz

Classify the objects below according to their magnetospheric type (4 min)

Object	Intrinsic	Induced	None
Sun			
Mercury			
Venus			
Earth			
Moon			
Mars			
Asteroid			
Jupiter			
Europa			
Ganymede			
Saturn			
Titan			
Enceladus			
Uranus			
Neptune			
Pluto			
Comet			

Questions

1. (T/F) Intrinsic magnetospheres are larger than induced magnetospheres, relative to the size of the planetary body

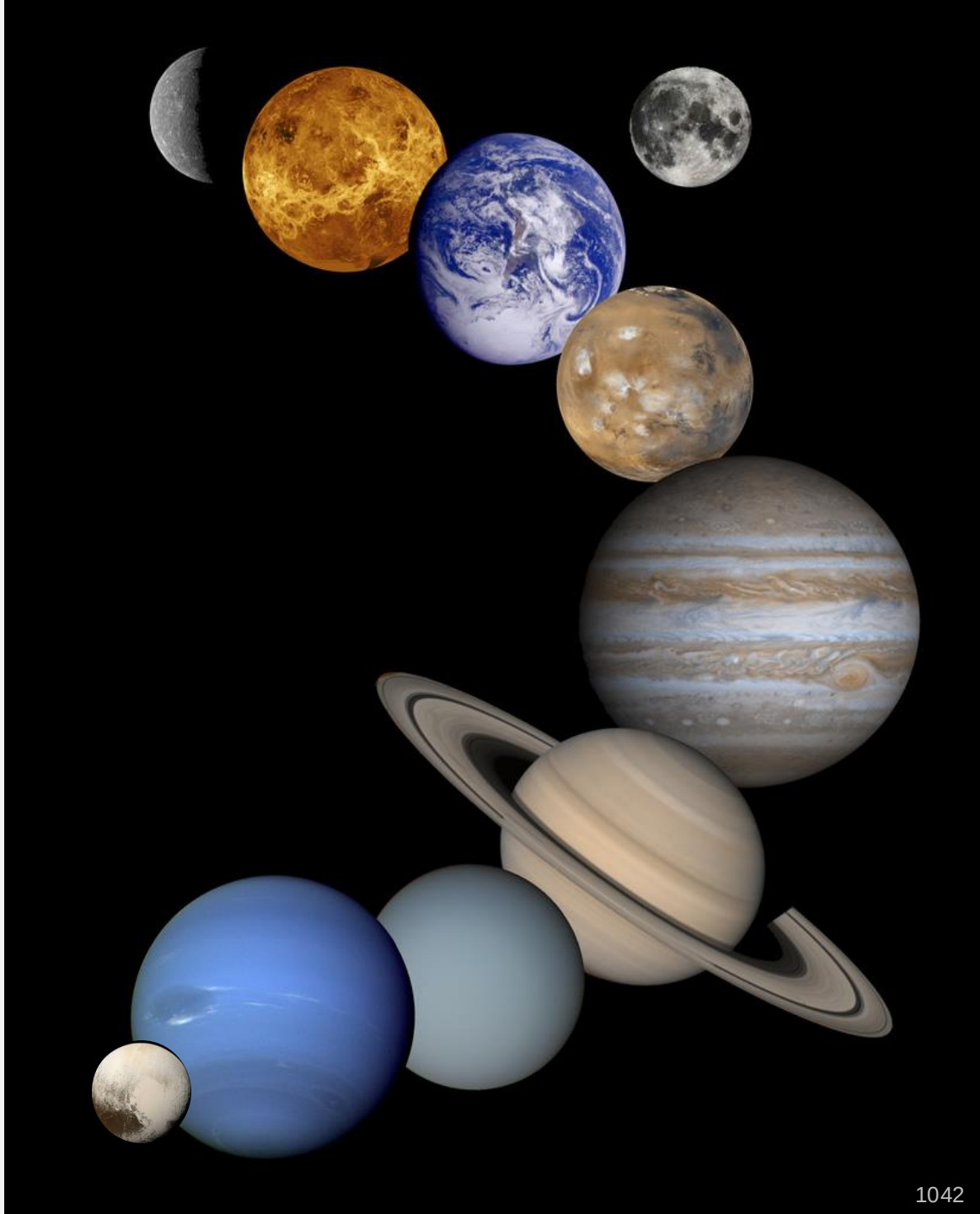
2. Jupiter's magnetic field strength at the cloud tops is **larger / smaller** (pick one) than Earth's surface field strength by a factor of ____.

3. (T/F) A single object can change its magnetospheric "type" over time.

2. Comparative Solar System Atmospheres

Question

How many of the objects at right possess atmospheres?



There are many ‘kinds’ of atmospheres in the SS today

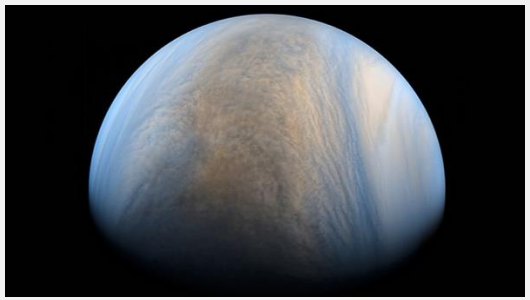
Major terrestrial ‘planet’ atmospheres
Venus, Titan, Earth, Mars

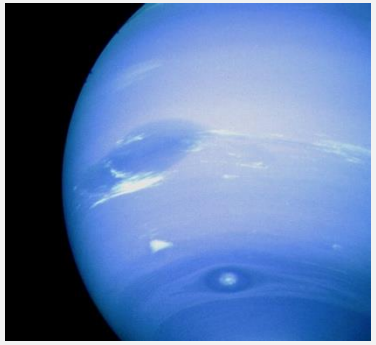
Giant planet atmospheres
Jupiter, Saturn, Uranus, Neptune

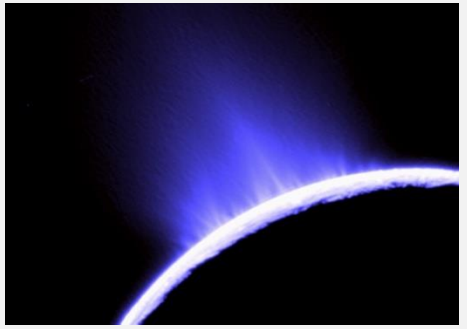
Tenuous atmospheres
Io, Triton, Europa, Pluto, Ganymede, Callisto, Enceladus

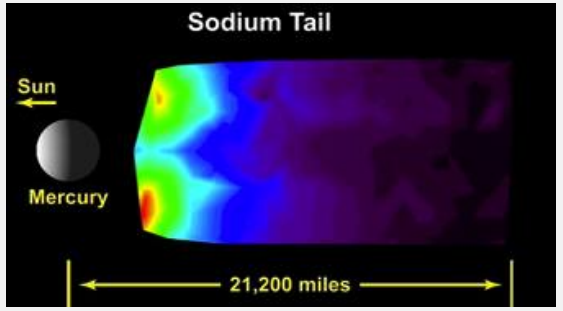
Cometary atmospheres

Surface-bound exospheres
Moon, Mercury









Primary vs secondary atmospheres

Primordial Atmospheres

- Captured gas from solar nebula
  (98% H and He, trace H_2O, NH_3, CH_4, …)

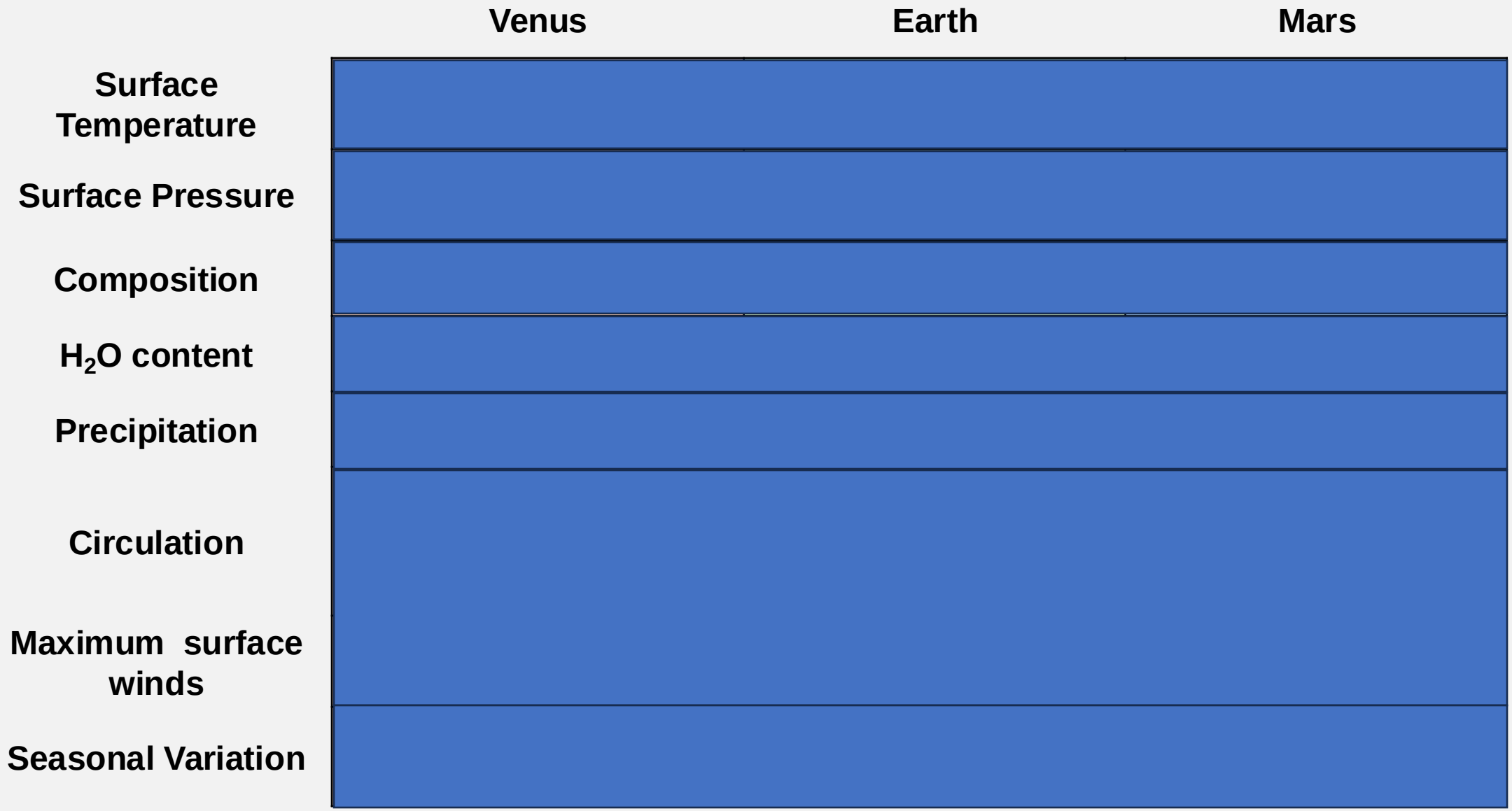
Atmospheric Blowoff

- Early atmospheres of terrestrial planets lost (had too much energy to be retained … more this afternoon)

Secondary (“current”) Atmospheres

- Outgassing from interior
- Volatile delivery from impacts
- Atmospheric chemistry

Contemporary climates of terrestrial worlds



3. Solar System Atmospheres Through Time

Question

What could you do to a planet to change its climate?

Come up with 4 (or more) fundamentally different answers.
You have 6 minutes

Action	Climate response

Four ways to change $T_{Surface}$

(assume today's SS TPs)

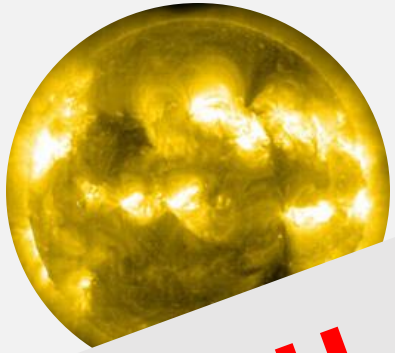
Global energy balance

$$\frac{S}{d^2}(1-A)\,\pi R_P^2 \;=\; \sigma T_{eff}^4\, 4\pi R_P^2$$

$$T_{surface}^4 \;=\; (\tau+1)\,T_{eff}^4$$

Radiative transfer

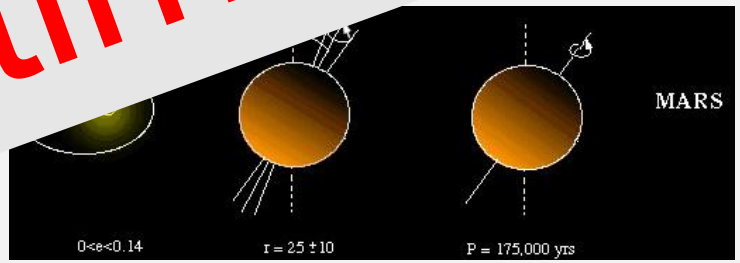
Solar Output



Planetary Albedo

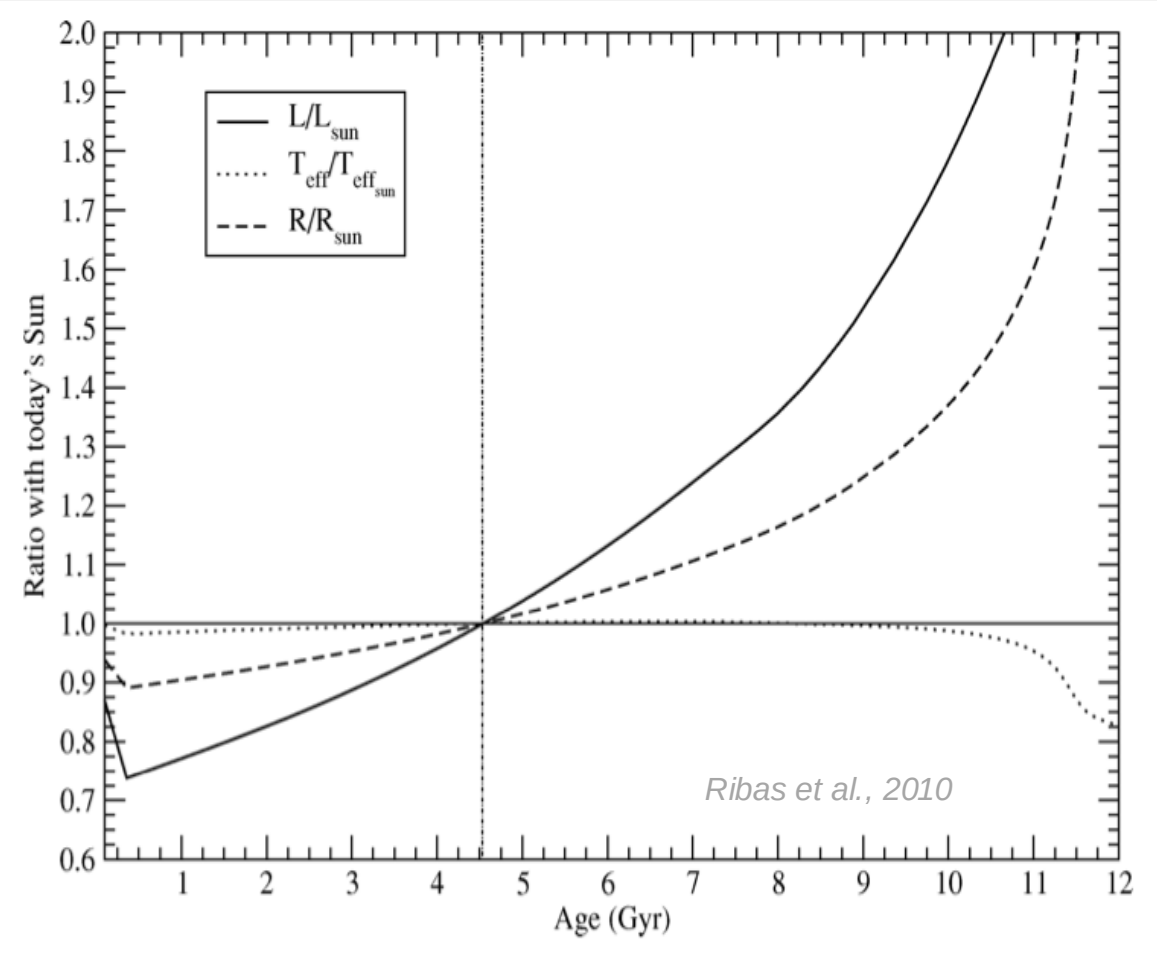
All change with time!

Greenhouse Gas Content



Planetary Orbital Elements

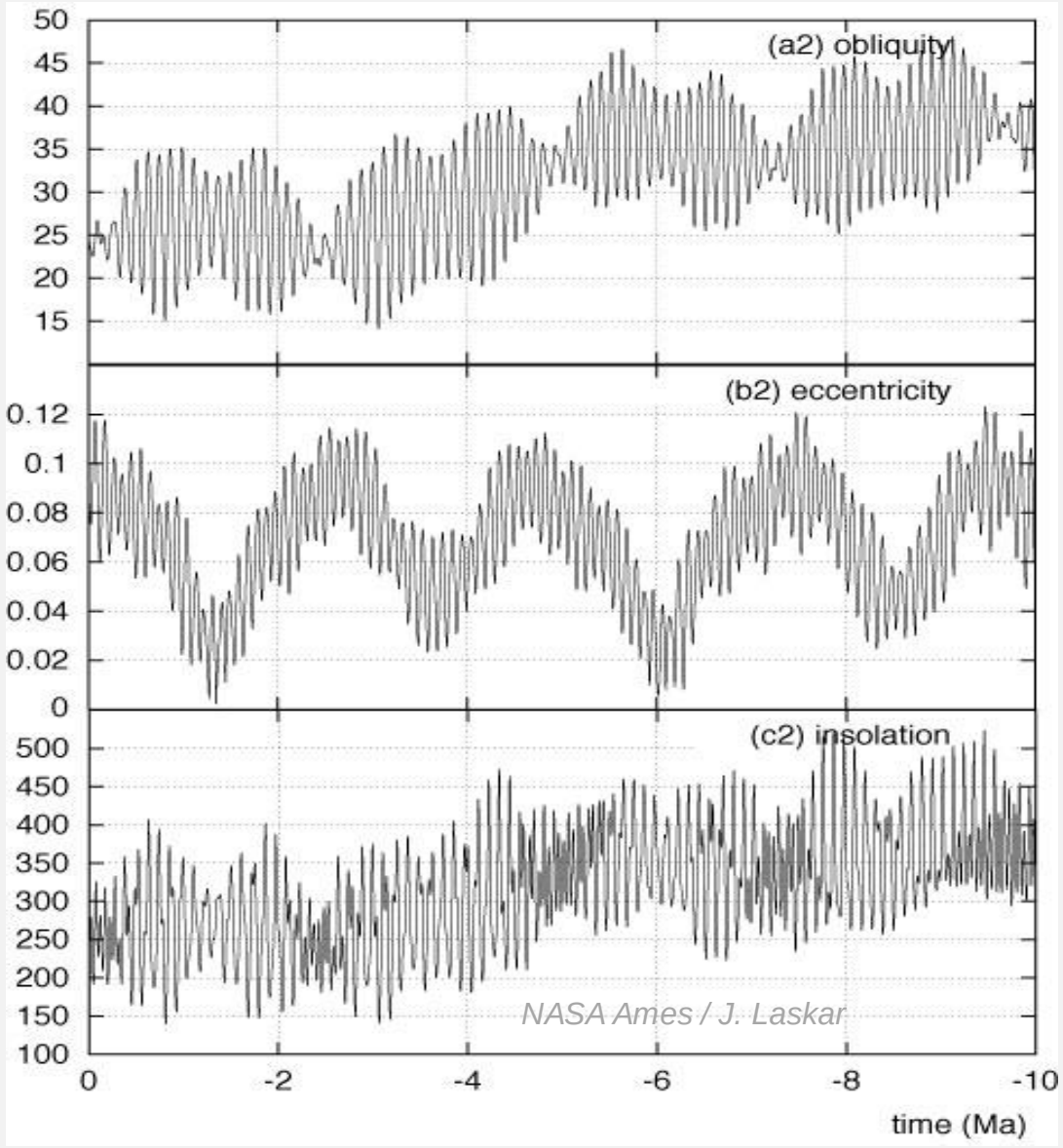
Solar output



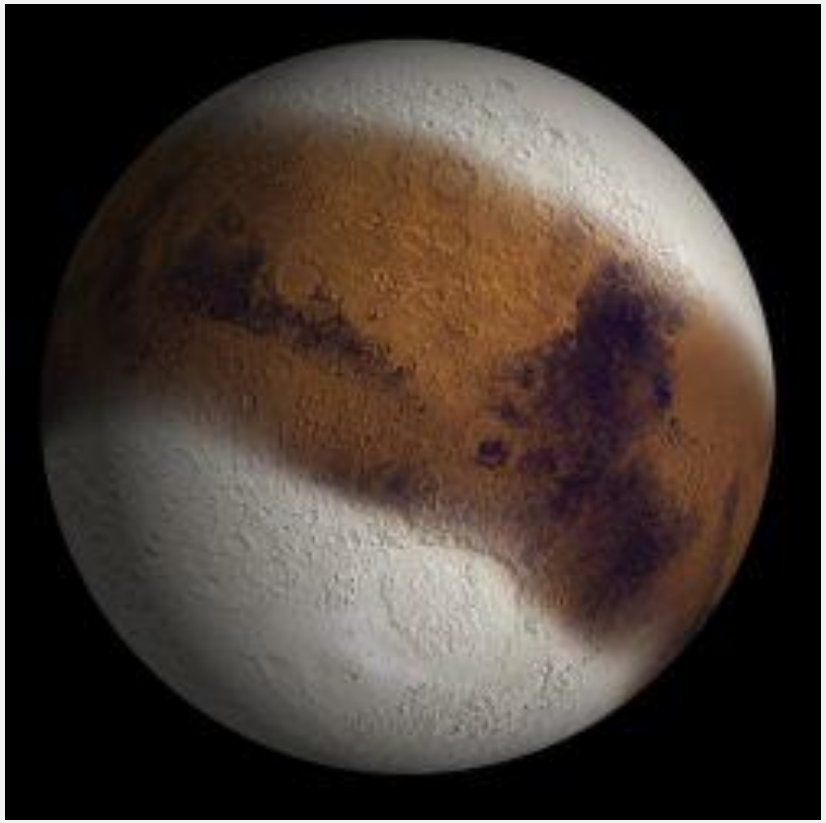
Total Luminosity

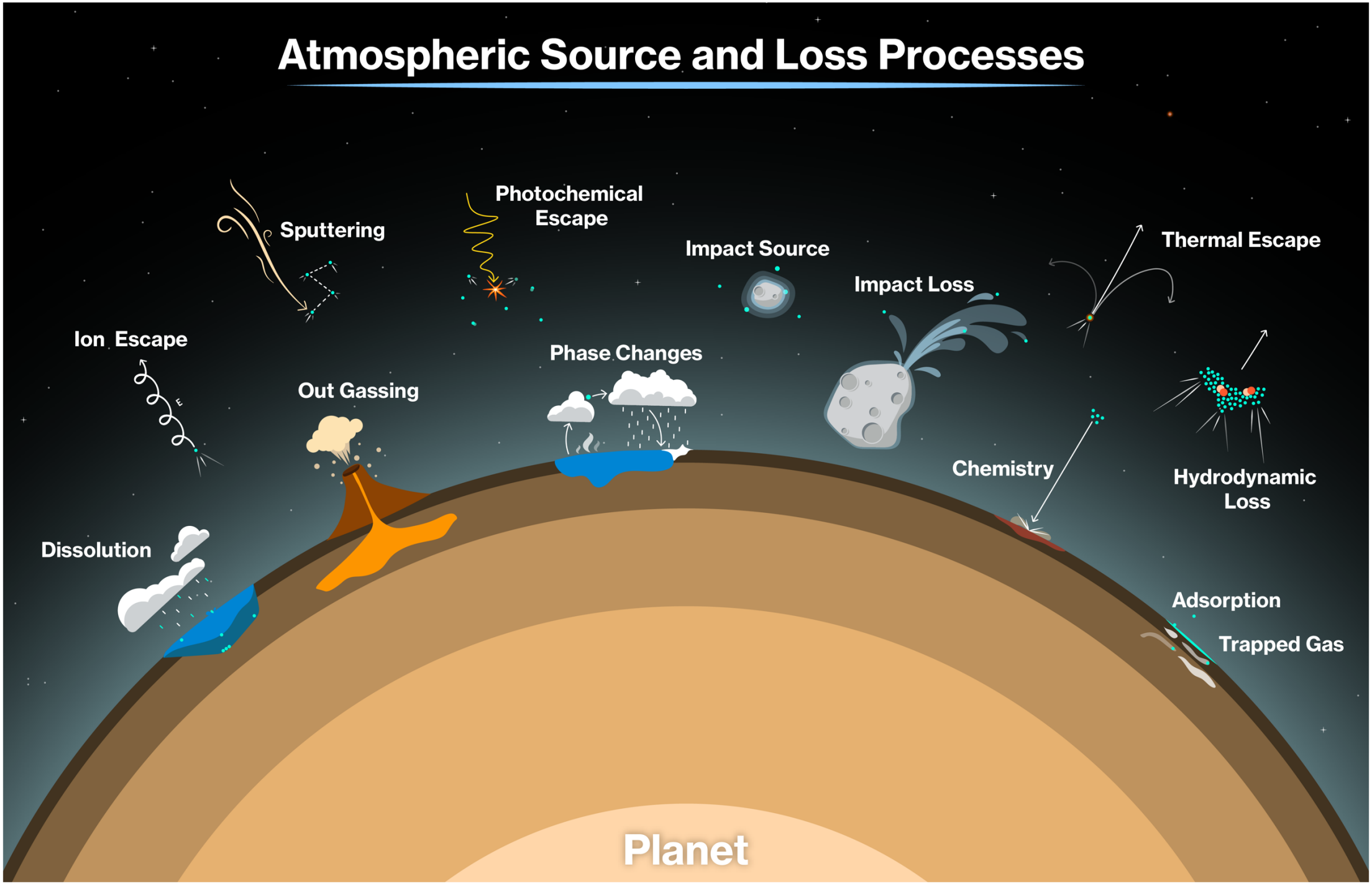
The Sun was 25-30% fainter long ago

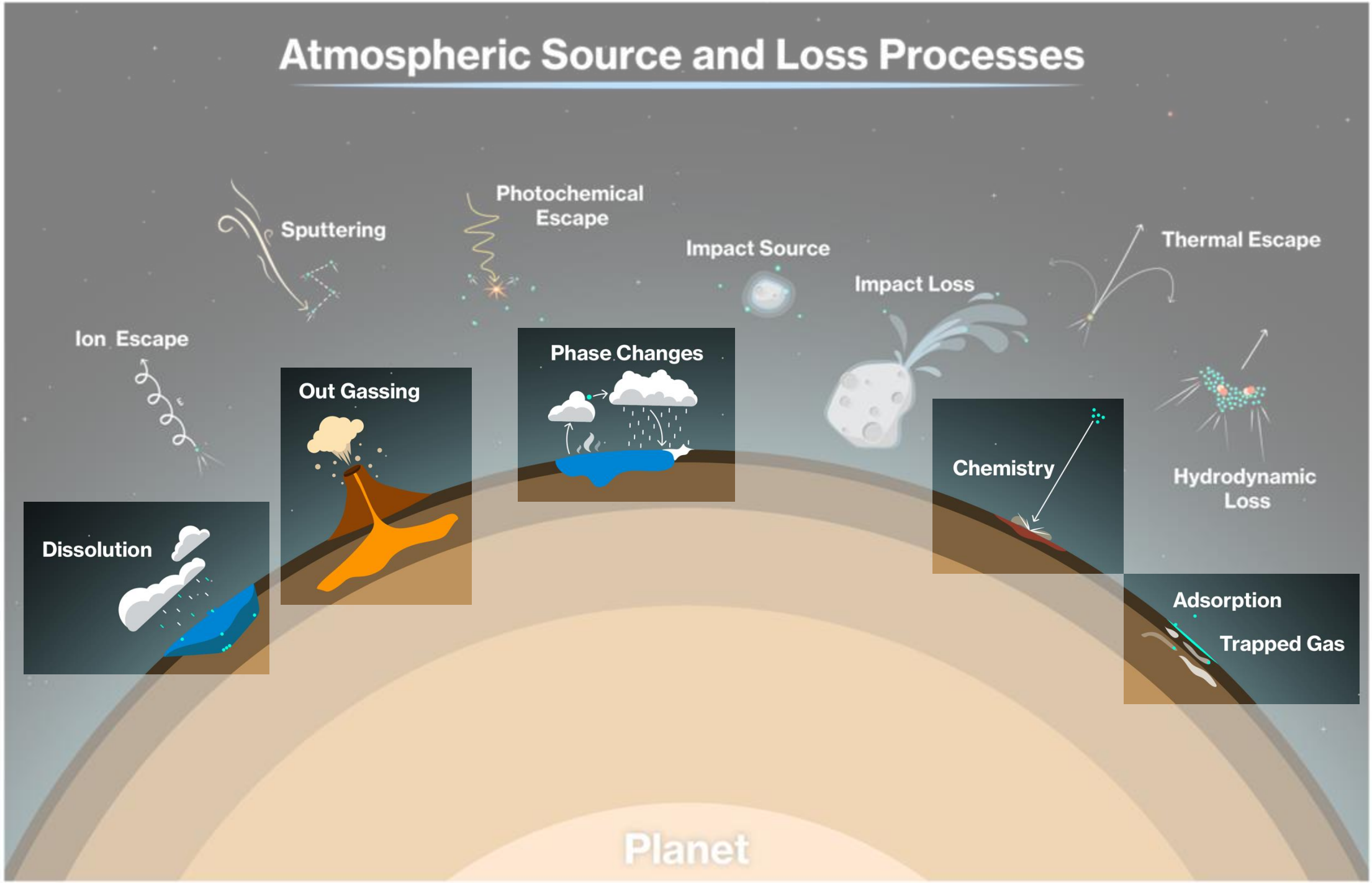
Planetary orbital elements



Mars tilt and eccentricity have led to periods of large and small polar caps (small and large atmosphere?)




Atmospheric Source and Loss Processes
Sputtering
Photochemical Escape
Impact Source
Impact Loss
Thermal Escape
Ion Escape
Phase Changes
Out Gassing
Chemistry
Hydrodynamic Loss
Dissolution
Adsorption
Trapped Gas
Planet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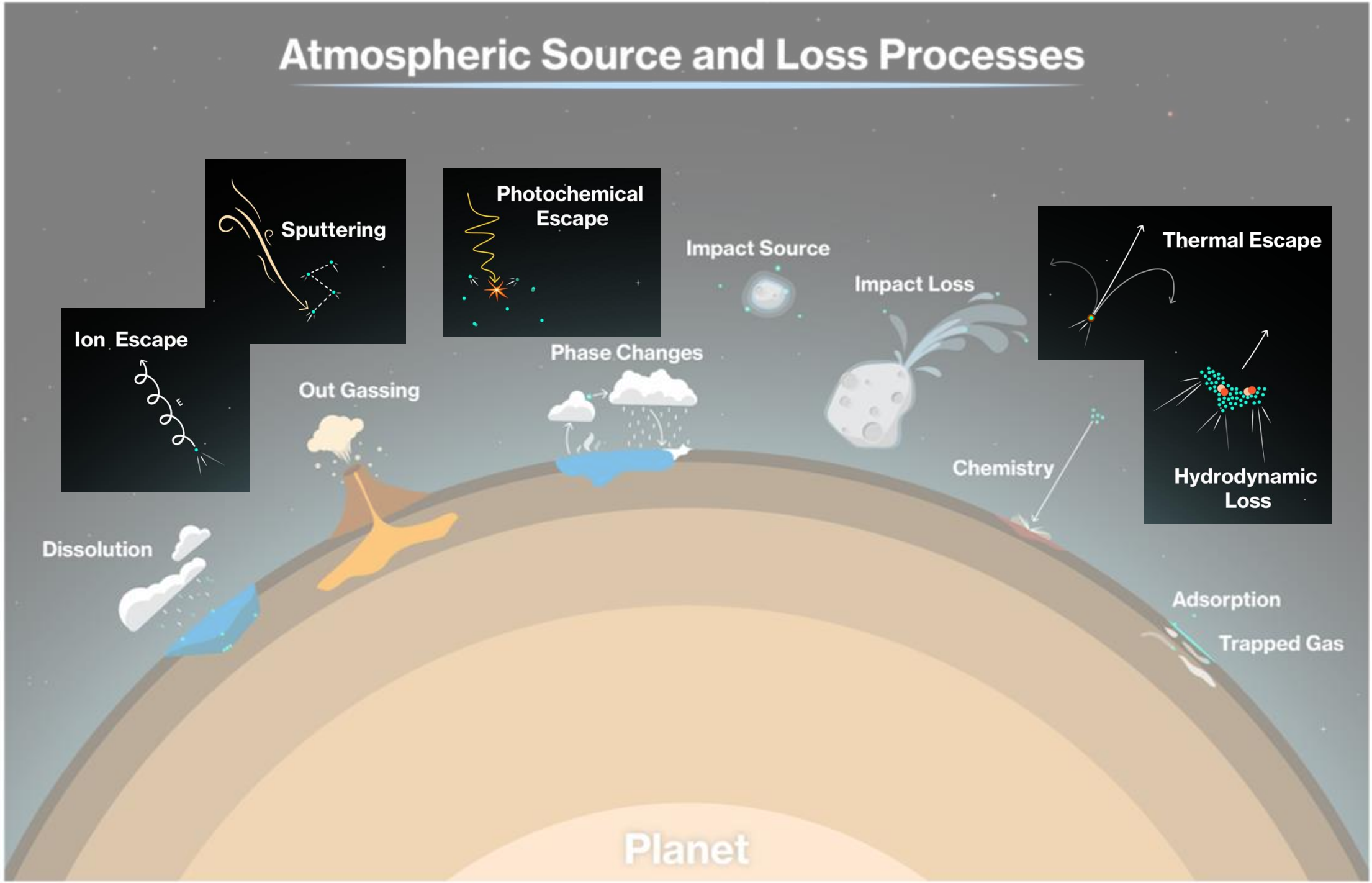
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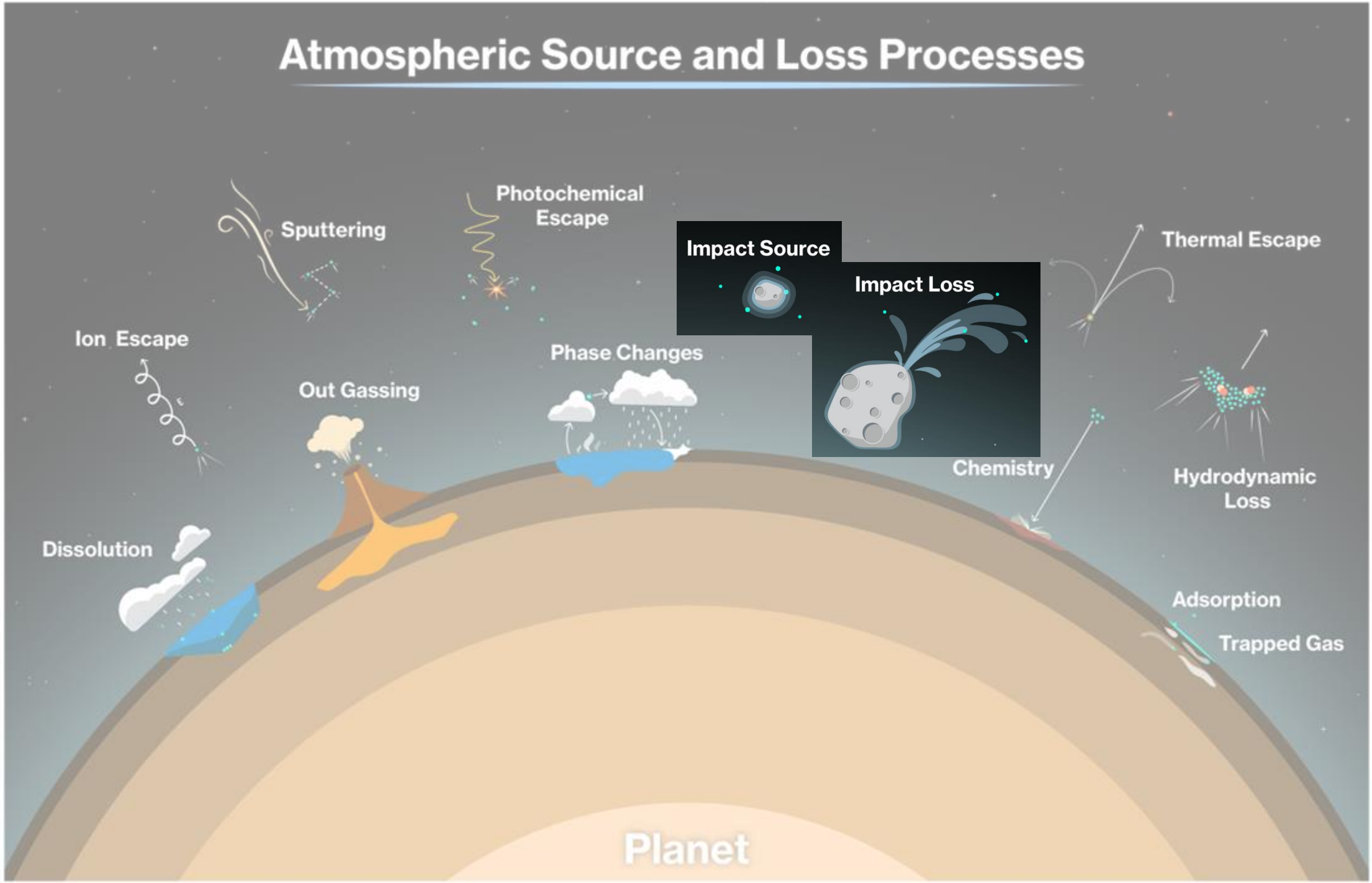
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Important concept interlude

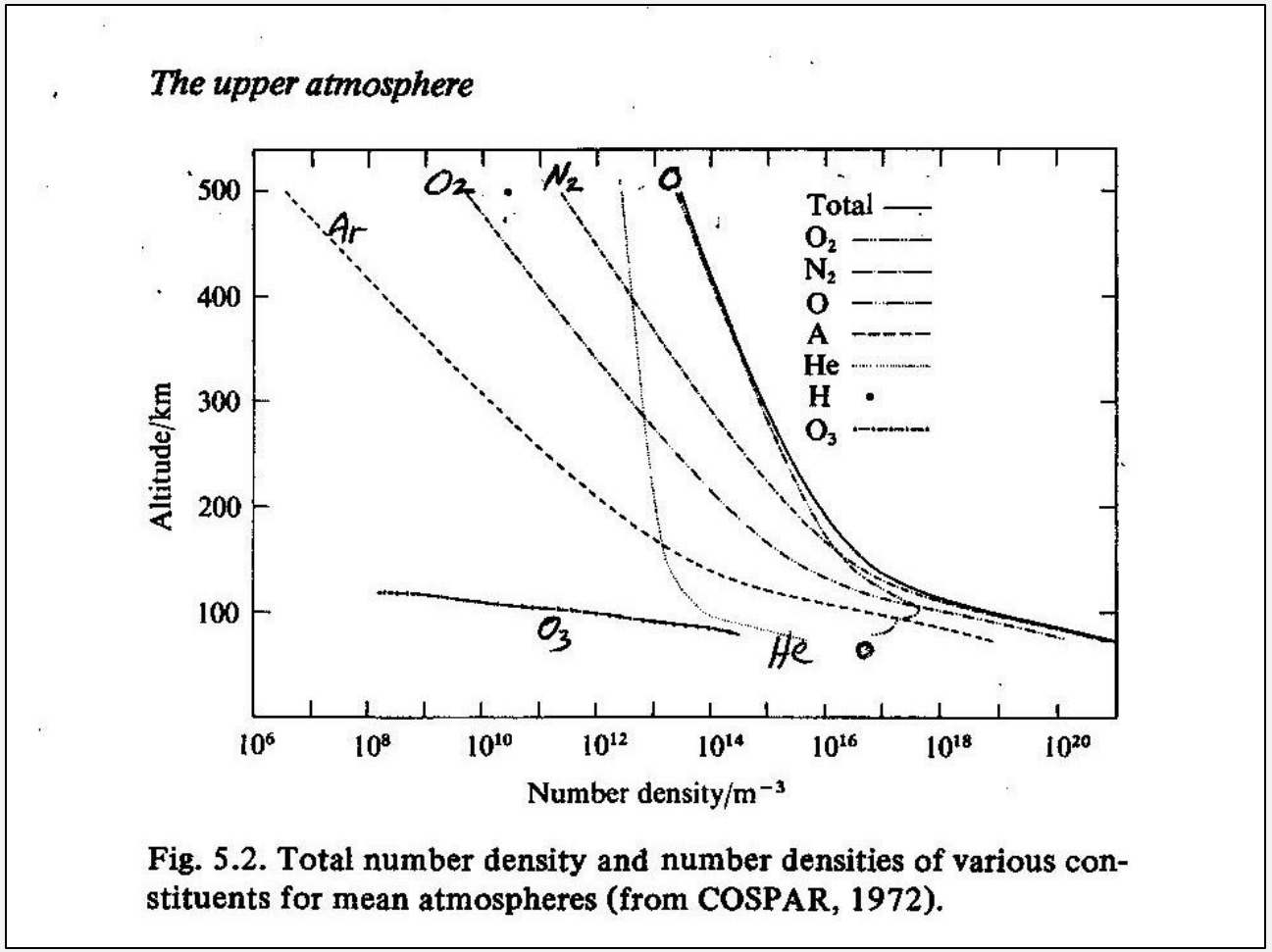
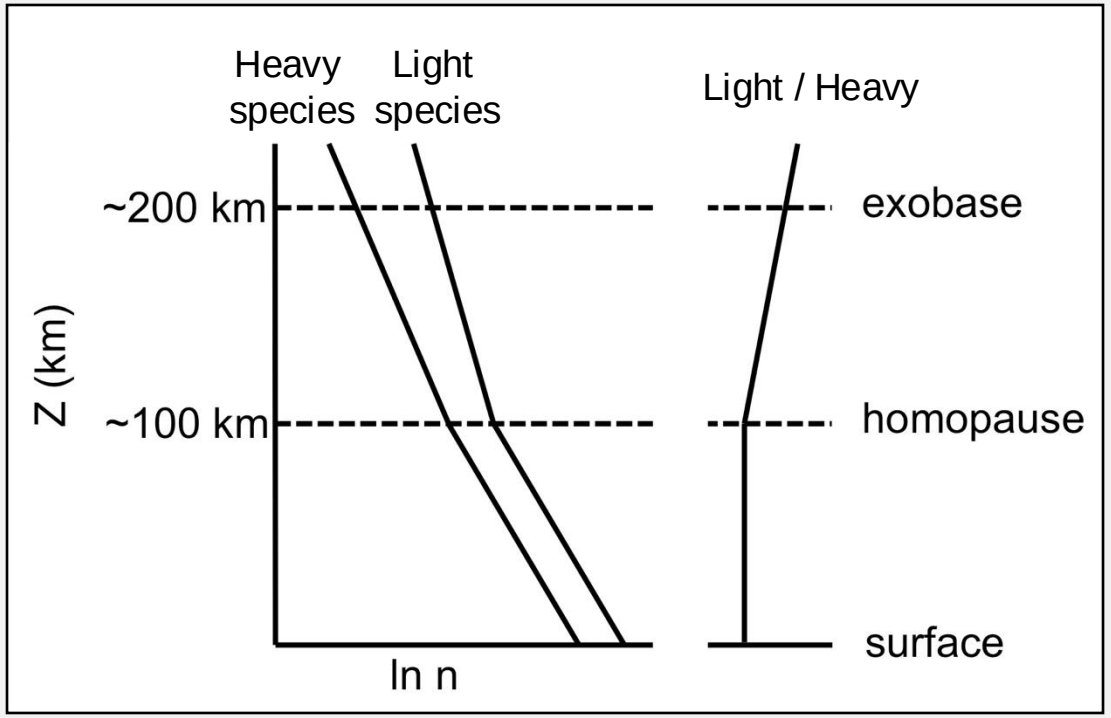


Fig. 5.2. Total number density and number densities of various constituents for mean atmospheres (from COSPAR, 1972).

Look at the decline of each species with altitude. There's a trend!

Important concept: Diffusive separation

- At high altitudes each species has its own characteristic vertical density structure ($H_i = {}^{kT}/_{m_i g}$)
- With less frequent collisions than the lower atmosphere, heavier species experience a stronger gravitational force and tend to ‘sink’
- This leaves the uppermost portions of an atmosphere enriched in lighter species
- This also means that the ‘mixing ratio’ (relative abundance) for each species varies with altitude in this region



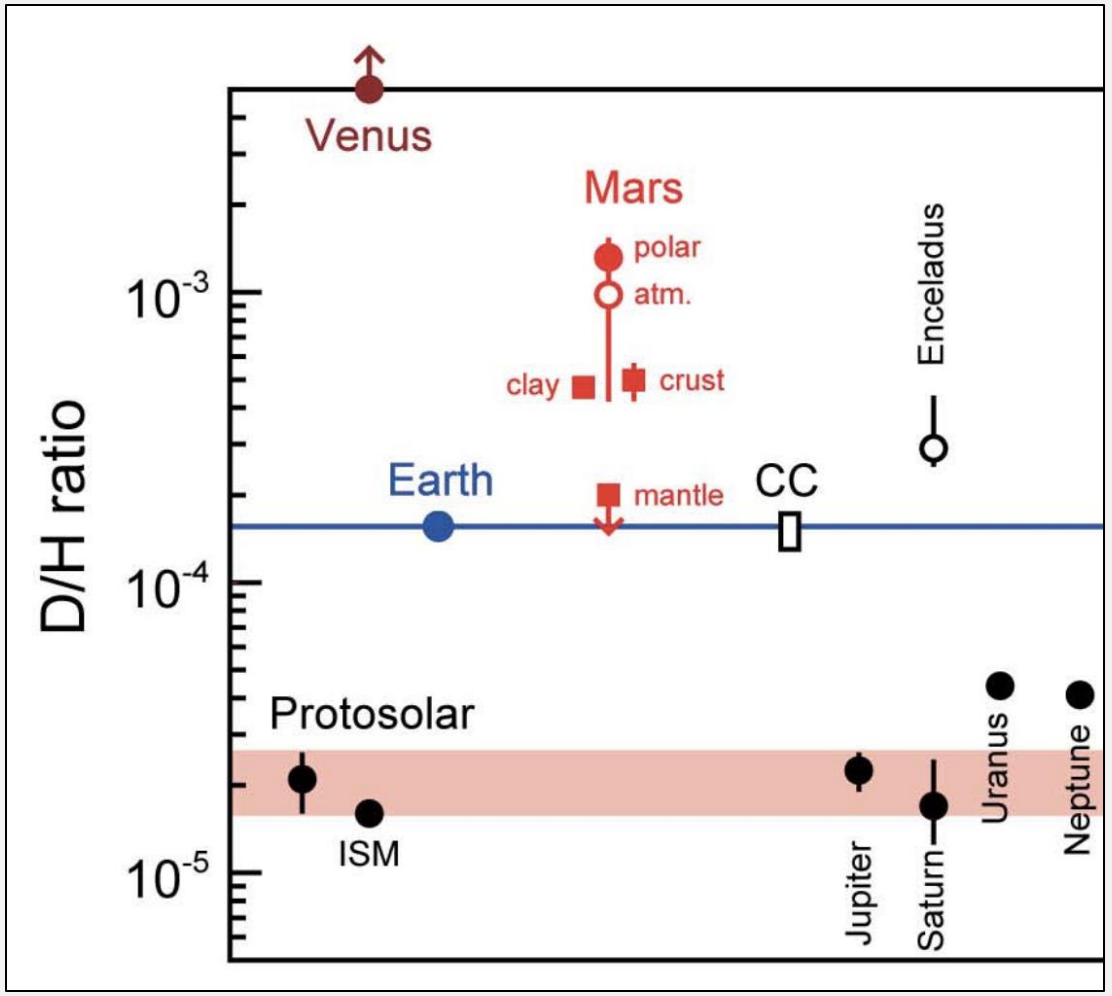
Diffusive separation and atmospheric escape

- Isotopes of a species differ only in mass – otherwise they behave in all the same ways
- The uppermost parts of atmospheres, where escape occurs are enriched in light isotopes

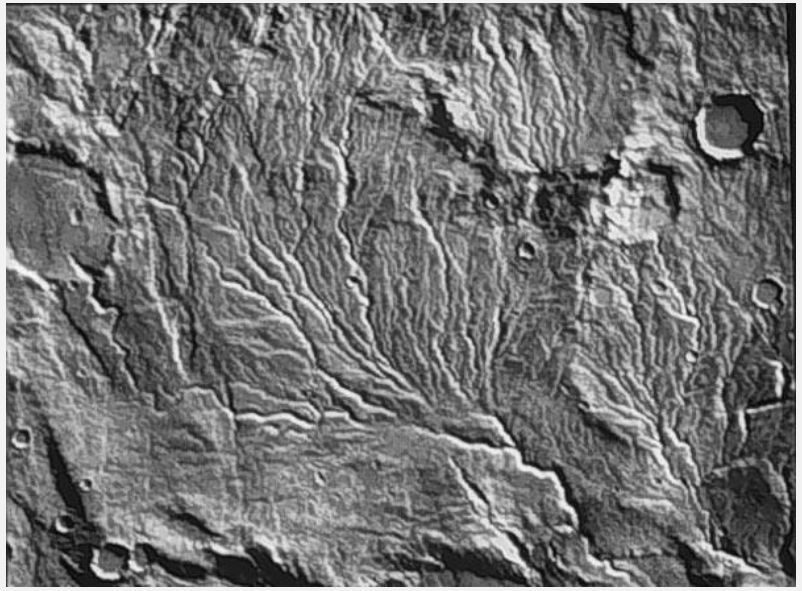
➢ Light isotopes should escape more readily than heavy isotopes

➢ Light isotopes also escape more readily due to the smaller mass

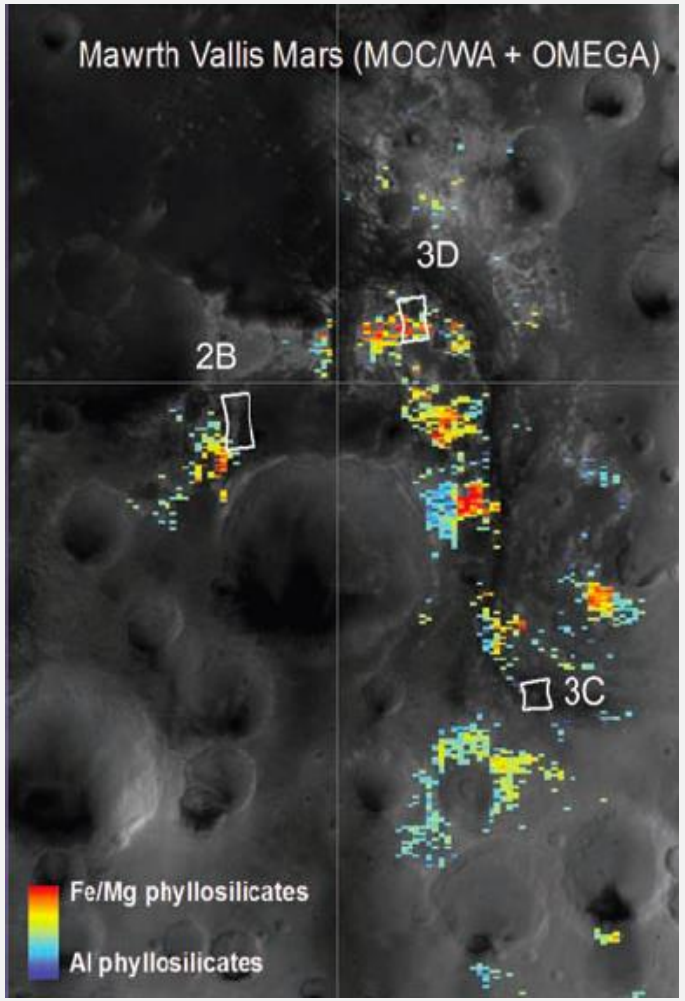
- Atmospheres where escape has been an important process should be enriched in heavy isotopes



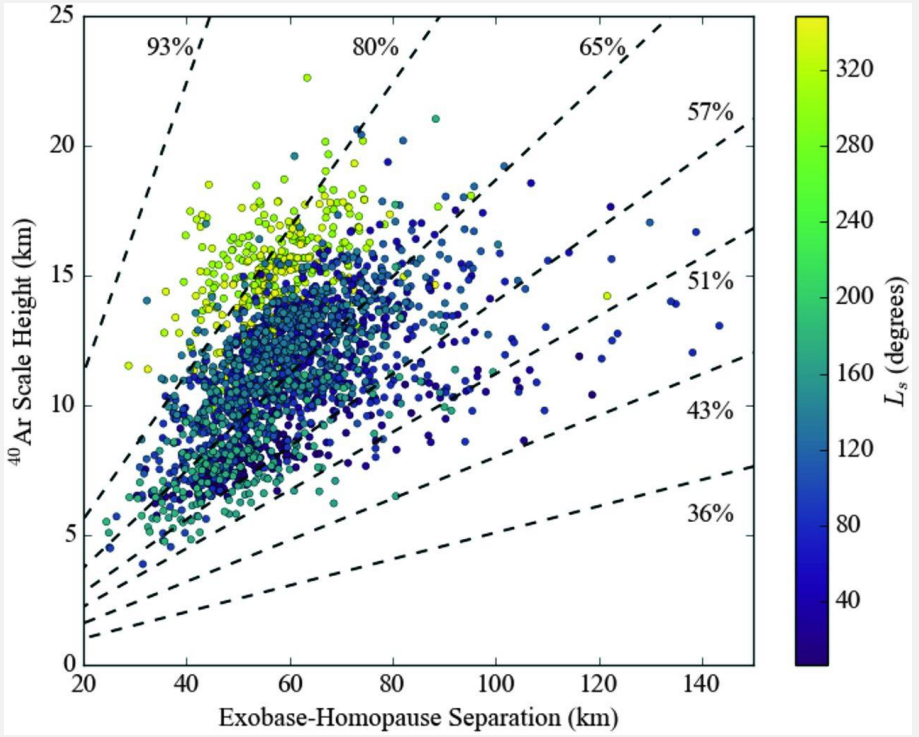
Evidence for climate change on Mars



Geomorphology

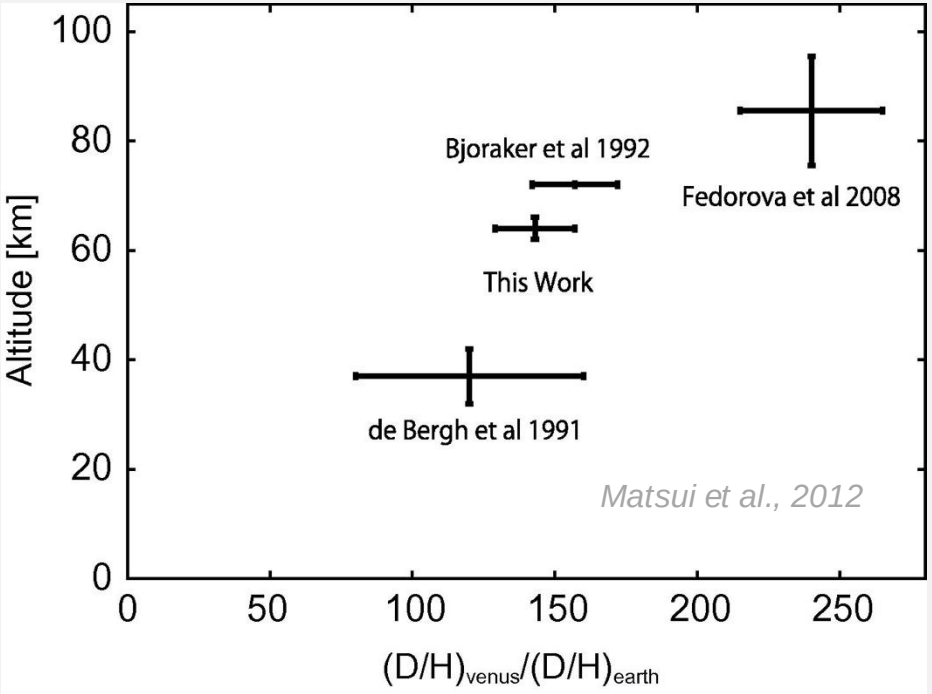


Geochemistry

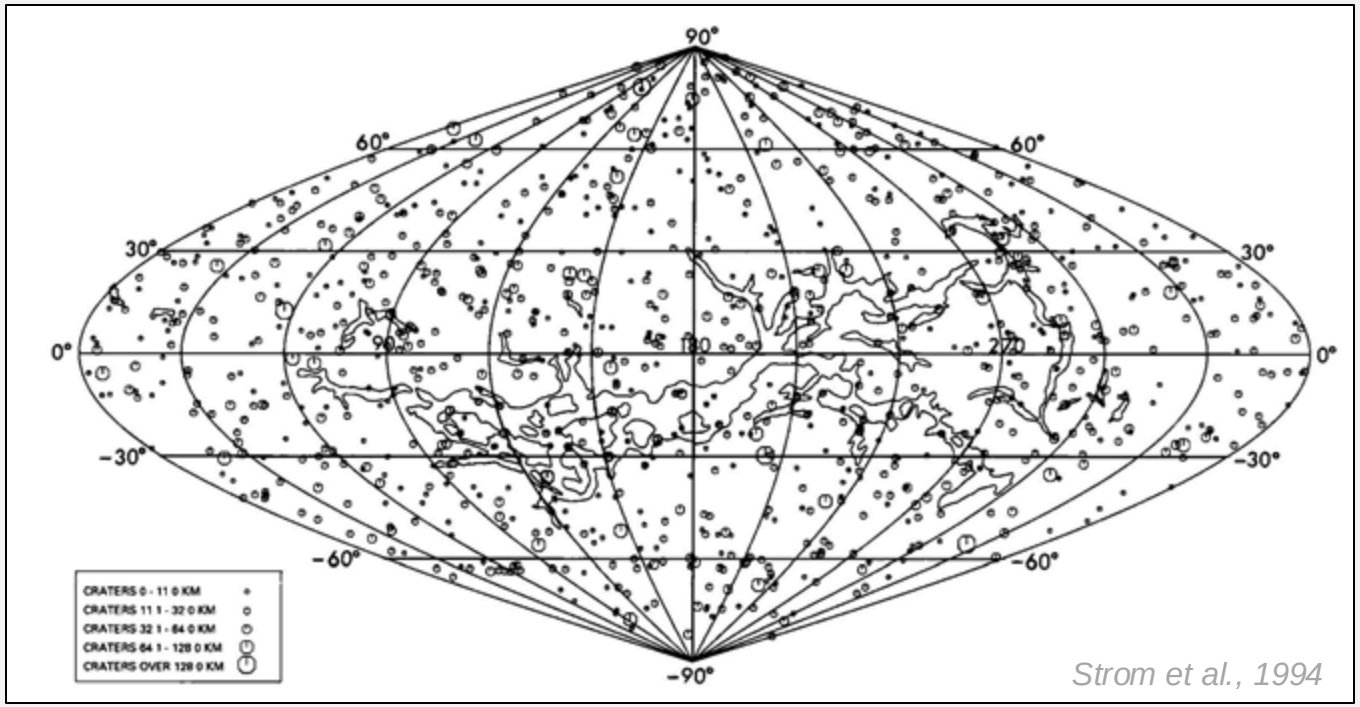


Isotopes

Evidence for climate change on Venus



Matsui et al., 2012



Strom et al., 1994

Evidence for climate change on Earth

100's-1000's yrs

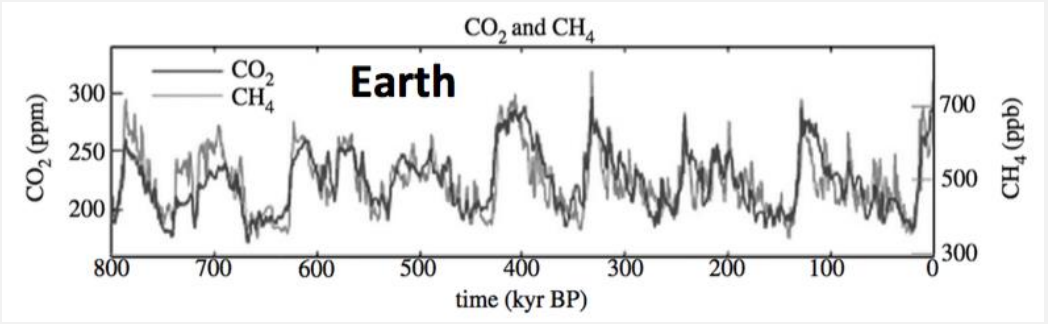
Trees and Coral
- Separation → growth rate → climate

100,000's yrs

Ice
- Bubbles → composition
- Isotopes → temperatures
- Pollen → conditions

>1 million yrs

Sediment
- Fossils / pollen → conditions
- Composition → temperature
- Layering → climate shifts
- Texture → environment



Why is Earth different from Venus and Mars?

The terrestrial planet atmospheres should have formed the same way – so we expect them to be similar. But…

- Earth has lots of water, and oceans

  Water escaped from Venus (too hot), and escaped from Mars or is trapped in the polar caps & subsurface

- Earth has little atmospheric CO_2 relative to V&M

  CO_2 dissolved in the ocean and formed carbonate rocks. ~175,000× less CO_2 remains in the atmosphere

- Earth has lots of N_2 and O_2

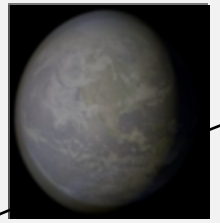
  N_2 was left after the CO_2 was removed. O_2 came from life! It would disappear quickly without life.

- Earth has a stratosphere

  Ultraviolet light transforms O_2 into ozone (O_3)

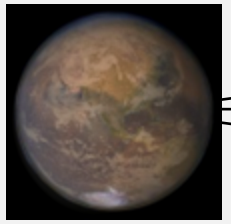
Divergent climate histories

Close to Sun → warmer
H_2O evaporates
Positive feedback
Runaway greenhouse



H_2O dissociates
H lost to space
O lost to space and surface

Thick secondary CO_2 atmosphere



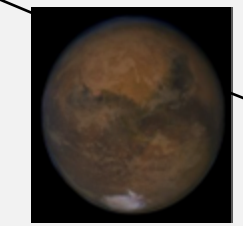
Surface H_2O removes CO_2 from atmosphere

Oxygen accumulates in atmosphere

Short term variations from orbit variation and other extreme events

Plate tectonics starts stabilizing CO_2 cycle

Greenhouse warming
Liquid H_2O at surface



Smaller planet → escape easier
Far from Sun → colder
Early thick atmosphere lost up & down