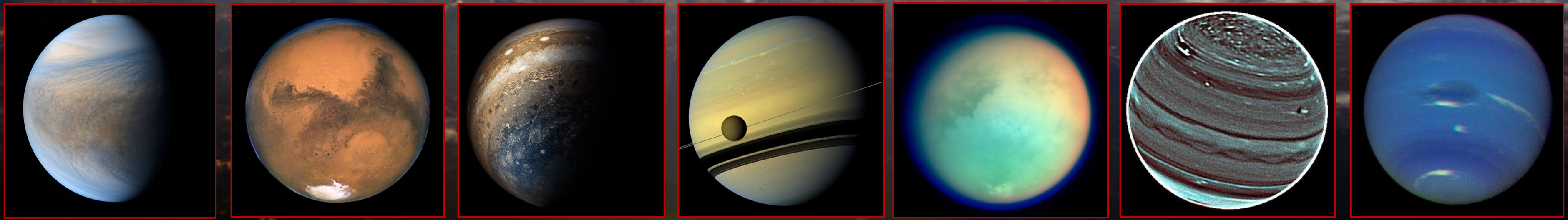
Lessons Learned from Solar System Exploration

(Defying Expectations since the 1960s)



UNIVERSITY OF LEICESTER

Prof. Leigh Fletcher
Planetary Science Group
School of Physics & Astronomy

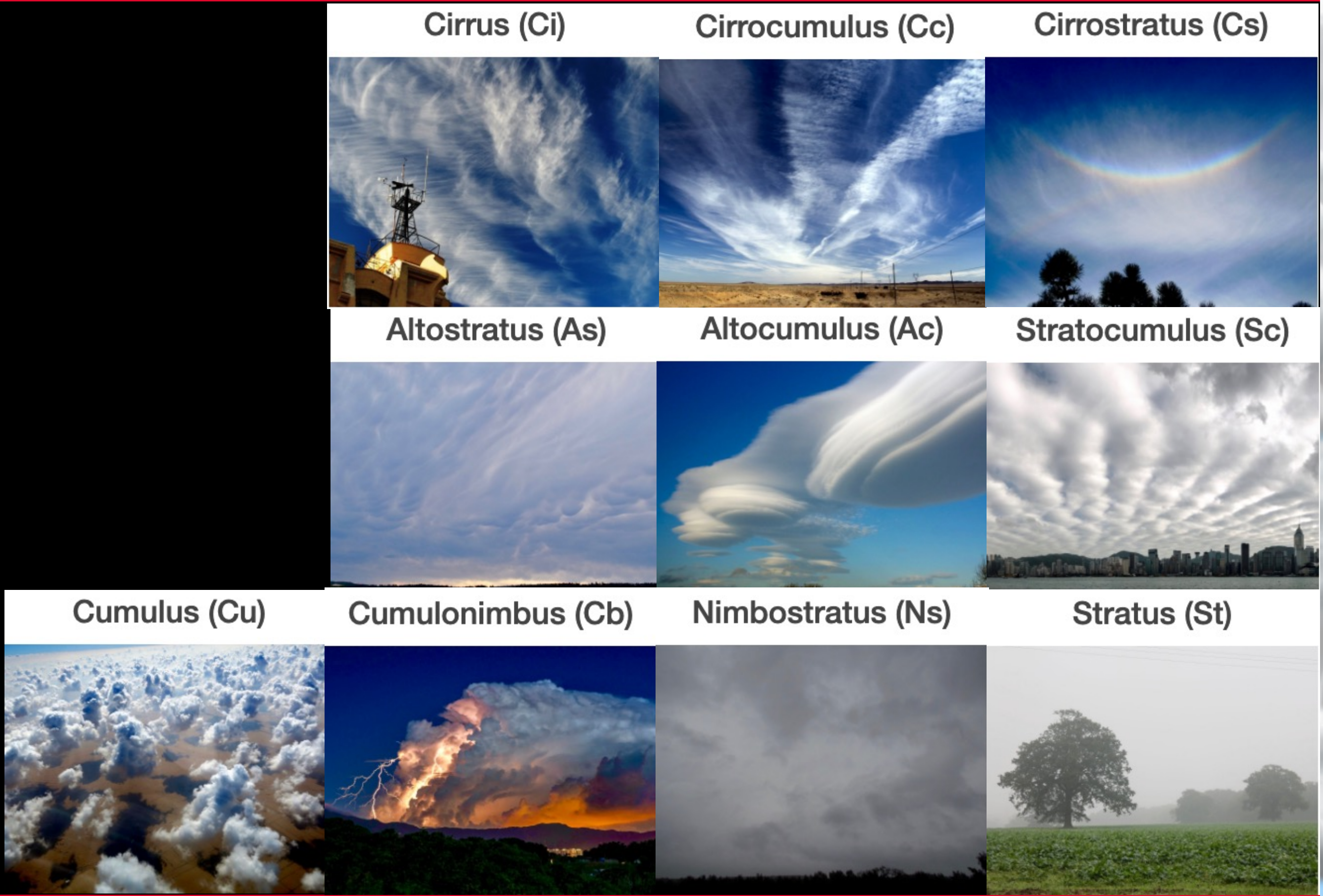
The problem of planetary atmospheres, so perplexing a few years ago, is now far advanced toward its solution.

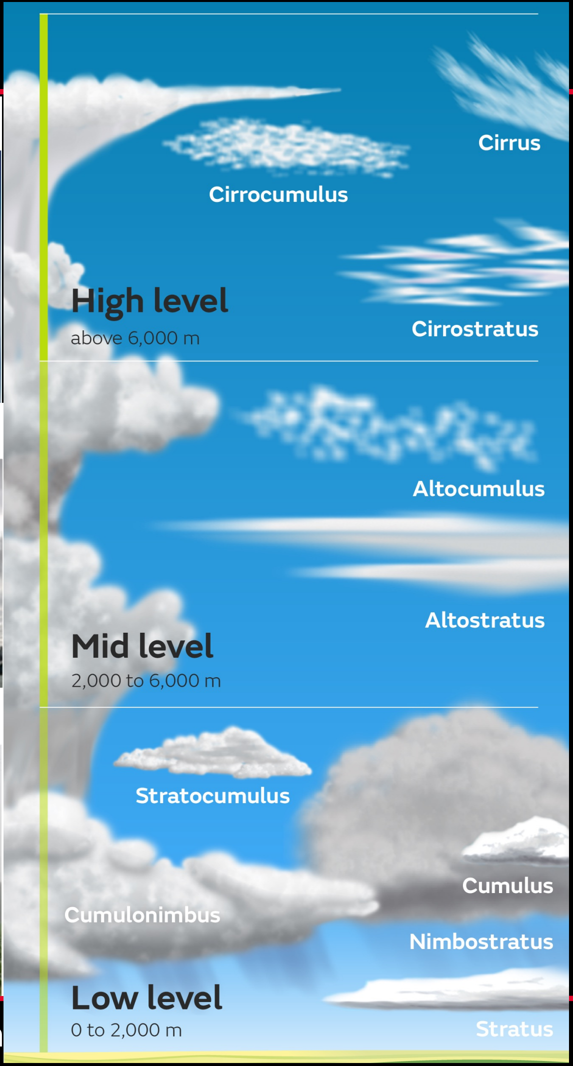
Toward its interpretation many of the sciences have contributed-astronomy, physics, chemistry, geology, biology and technology.

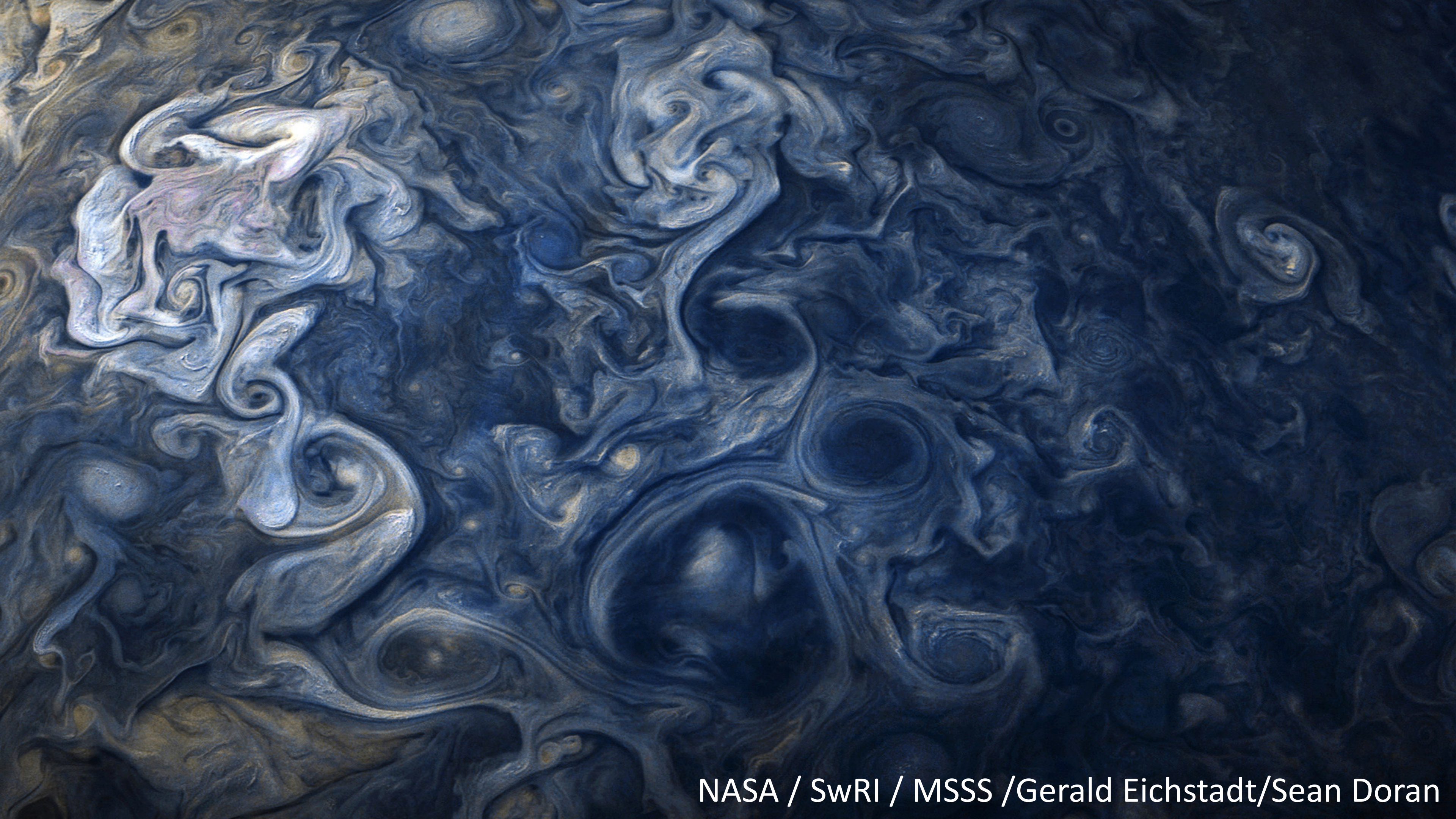
No one of them alone could have resolved the difficulties. It may, therefore, be appropriate that the attention of so general a scientific gathering may have been invited for a while to it: for it truly illustrates the old motto, "In union there is strength."

Henry Norris Russell (1935)

Earth: One Condensable – Huge Complexity

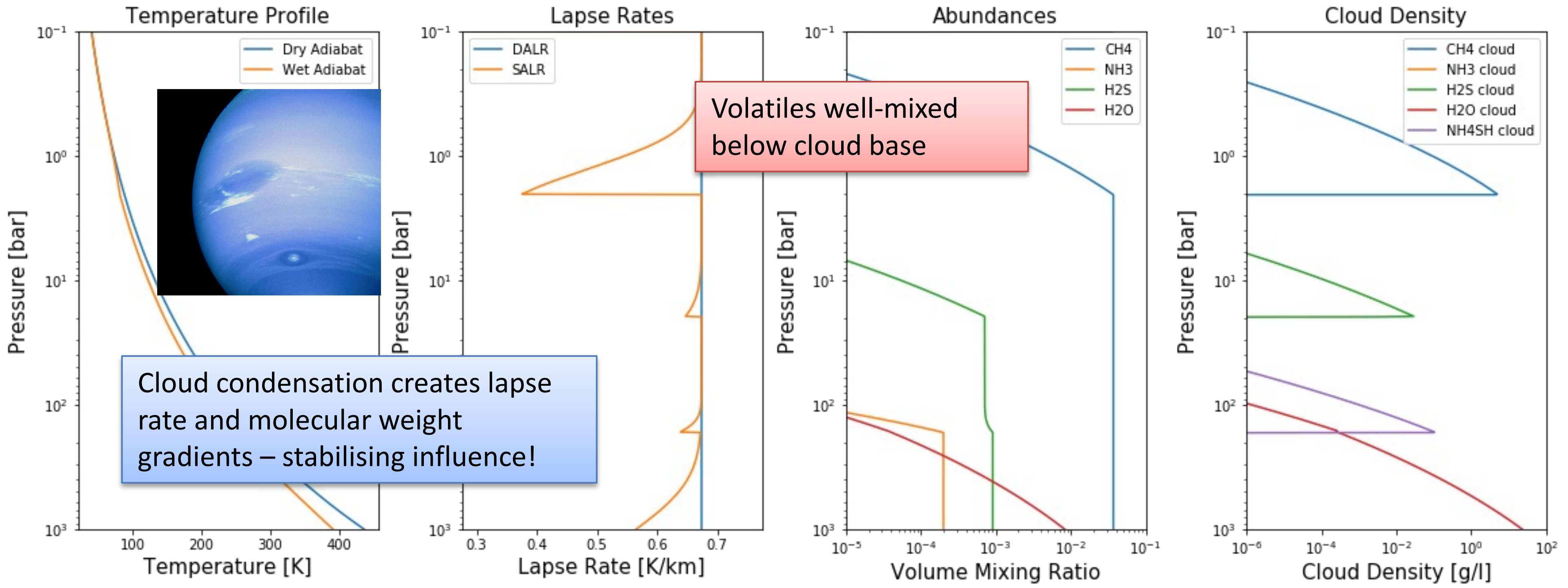






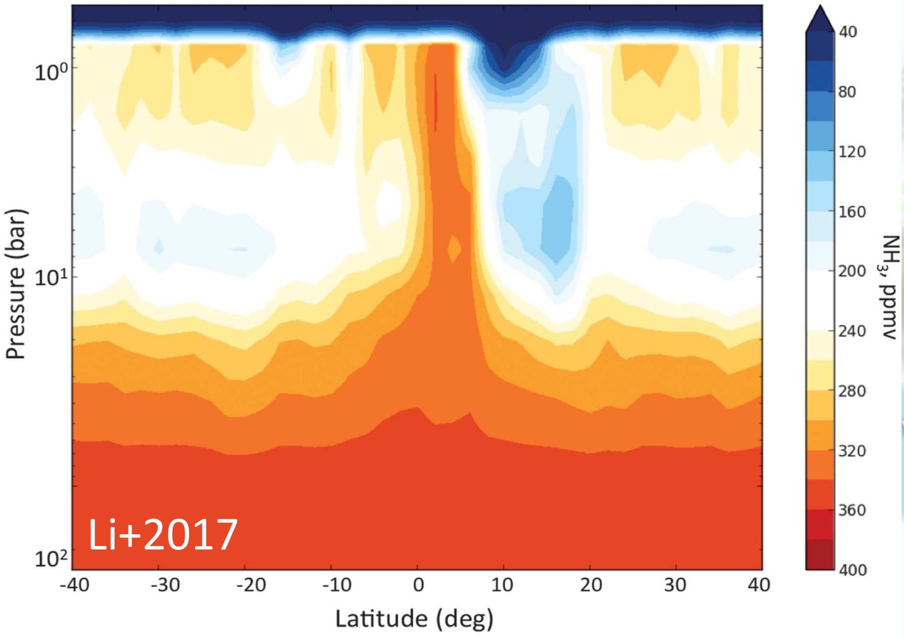
NASA / SwRI / MSSS /Gerald Eichstadt/Sean Doran

Giant Planets have Many Condensates

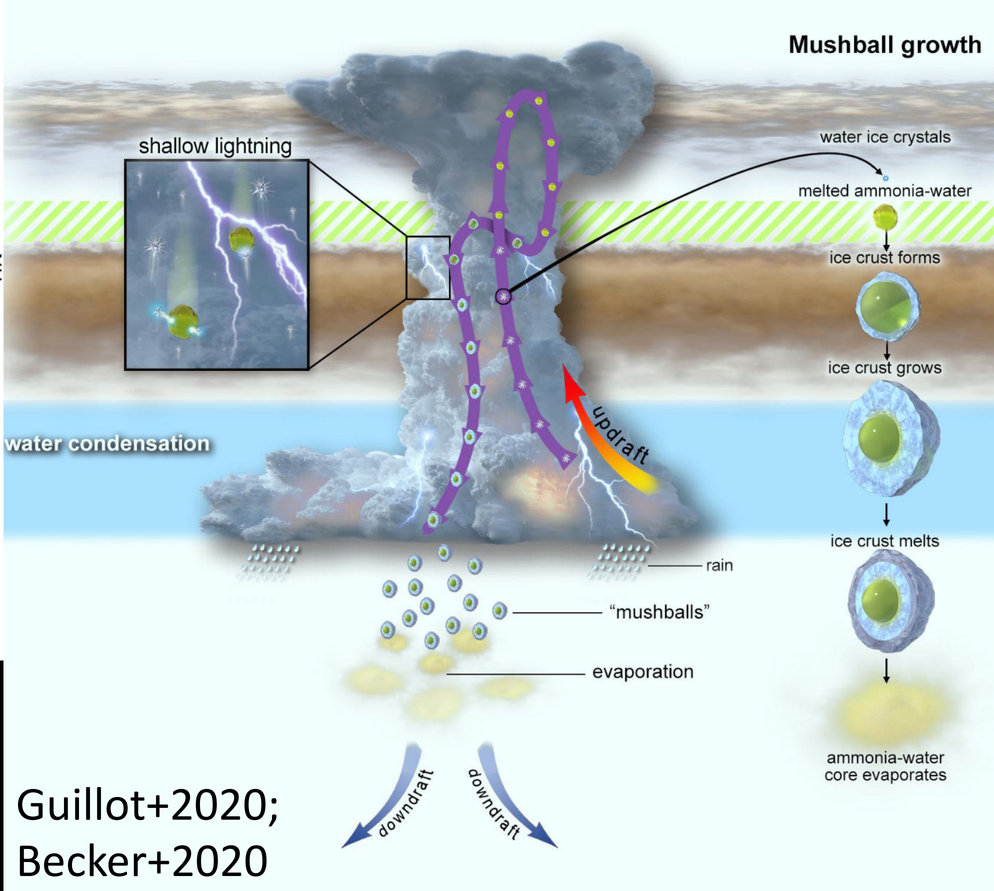


- Equilibrium Cloud Condensation Models (ECCMs) – almost never correspond to what we observe, but a decent first guess.

Volatiles are not well-mixed below cloud bases



- Juno shows NH_3 depleted to 40-60 bars.
- Exotic phases (mushballs!) may be important.



Disequilibrium is everywhere

Thermochemistry

H, He, C, O, N, S, P

Photochemistry

Disequilibrium chemistry

Volatiles:
CH_4
NH_3, H_2S, H_2O

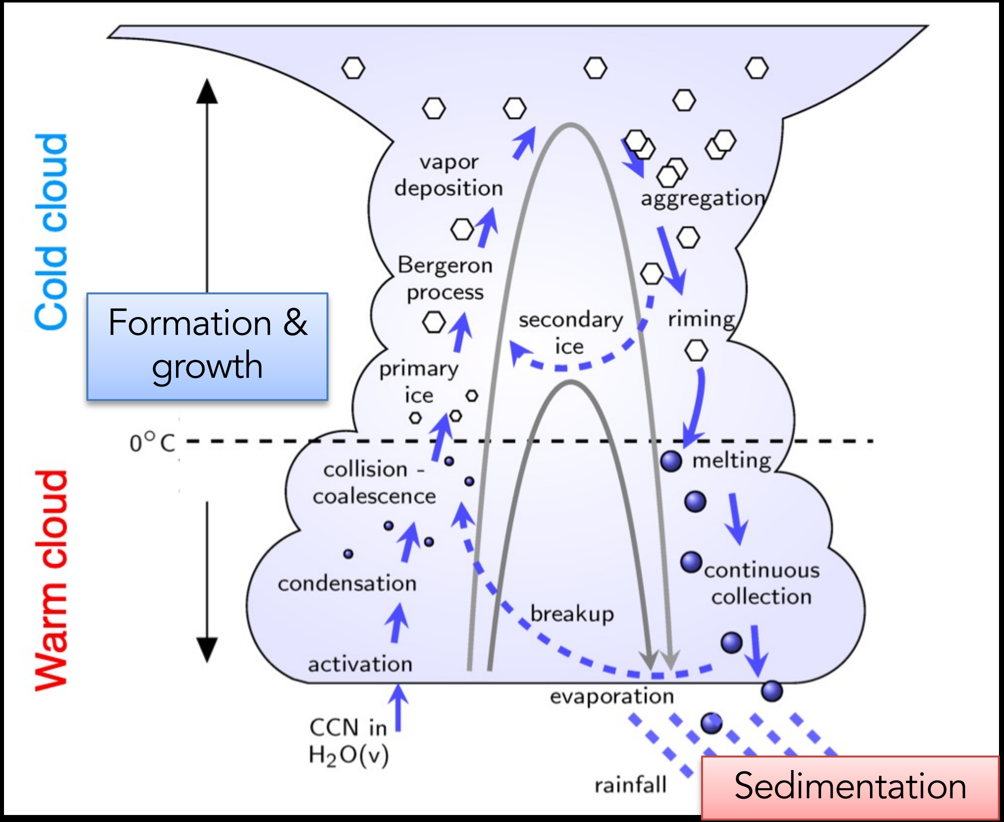
Photochemicals:
C_2H_2
C_2H_6
C_3Hx, C_4Hx…

Disequilibrium:
PH_3
AsH_3, GeH_4, CO
Para-H_2

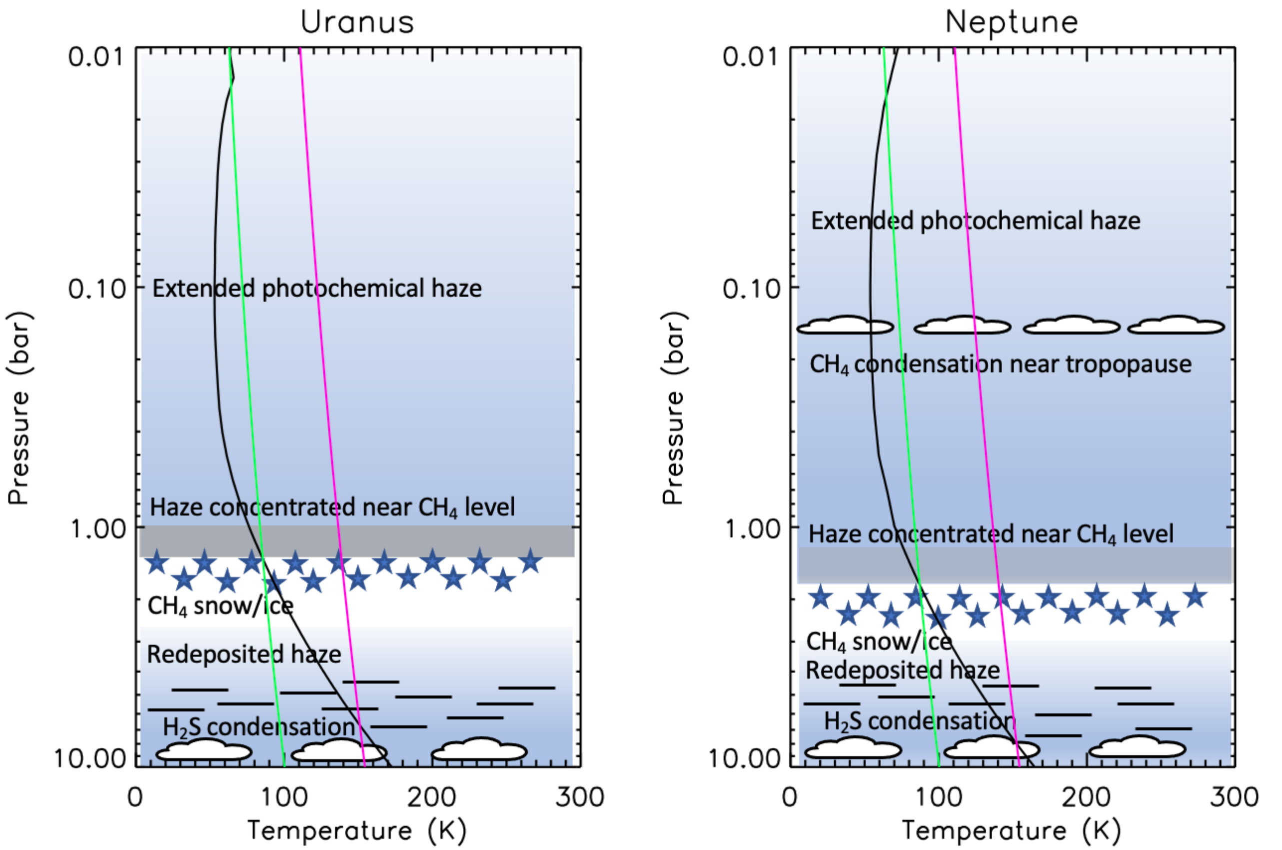
Exogenic:
H_2O
CO_2
CO

Cloud Condensation Nuclei & Microphysics are Key

- **Homogeneous nucleation** occurs when vapour condenses to form an embryonic particle upon which more vapour deposition occurs.
- **Heterogeneous nucleation** requires micron-sized **cloud condensation nuclei (CCN).**
- All largely ignored in spectral retrievals.

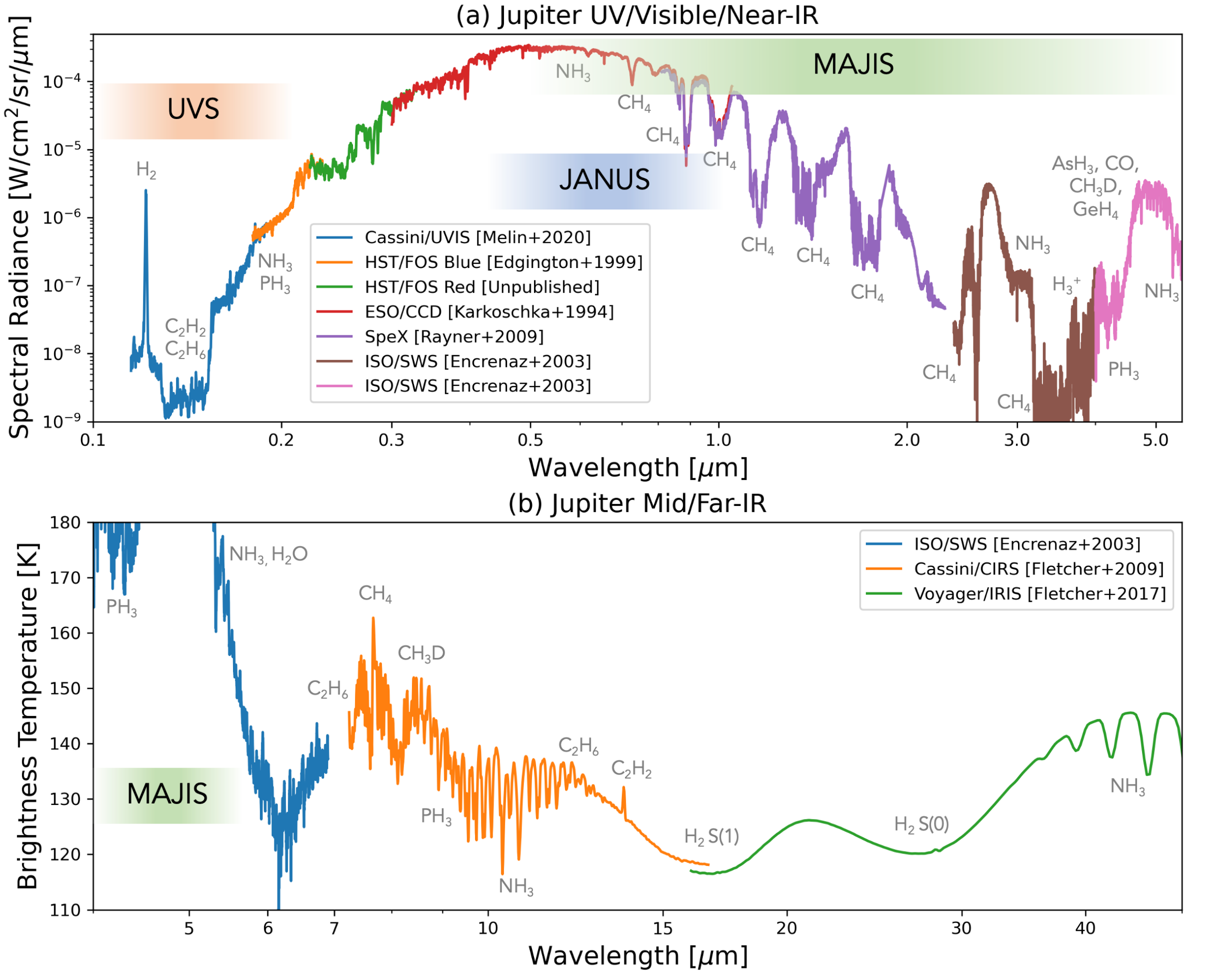


[Current] Holistic Model for Ice Giants



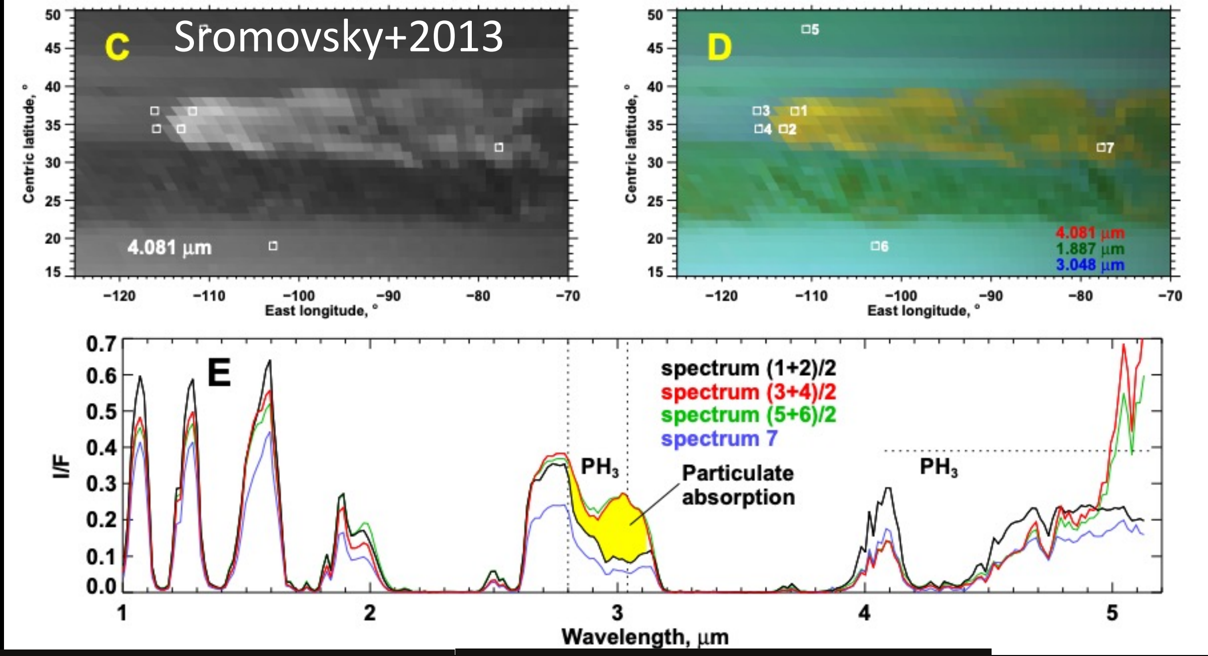
- Irwin+2022
- Photochemical haze in stratosphere.
- CH_4 stability barrier at condensation level
- Rapid methane condensation (snow).
- CH_4 evaporates at deeper levels releasing their haze core 'payload' to seed deeper clouds.

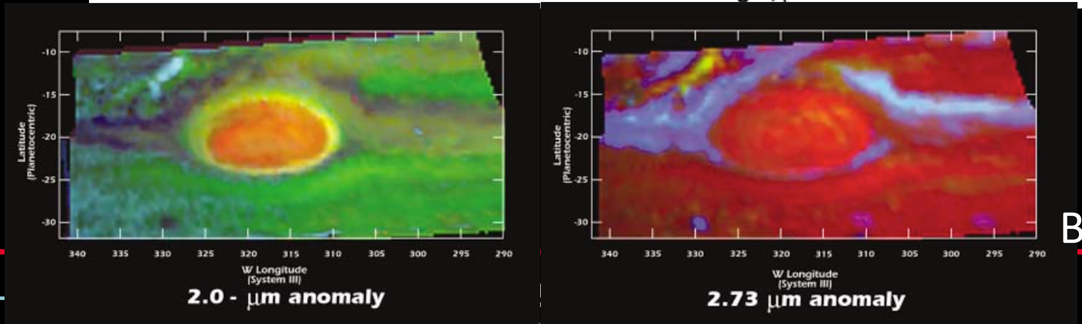
Spectral Retrievals are Degenerate



Limited signs of "fresh" ices

- Detection of "pure" NH_3 ice restricted to regions of strong convection on Jupiter/Saturn.
- Even then, unique signature of ices absent/masked.
- Composition remains very challenging.

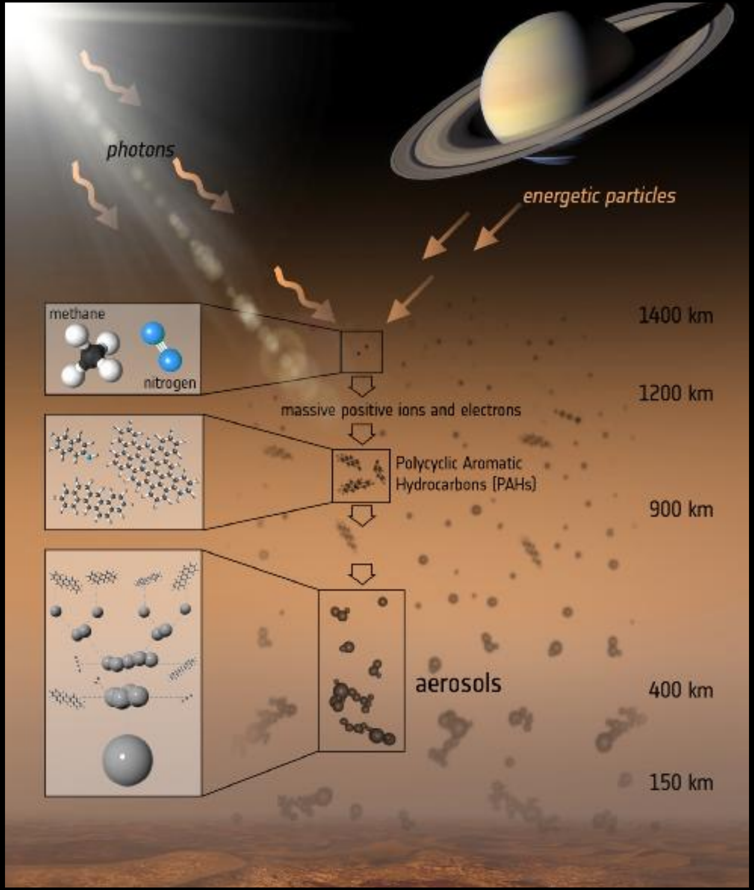


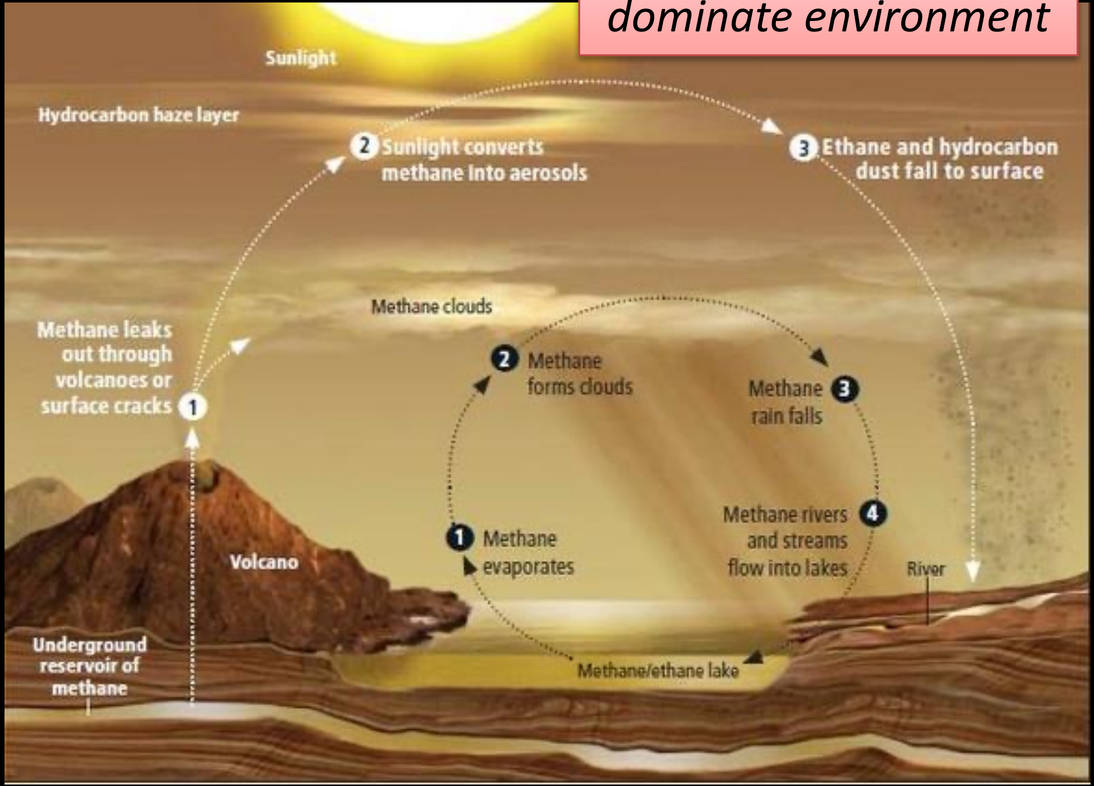


Baines+2002

Chemical Masking & Photochemical Hazes?

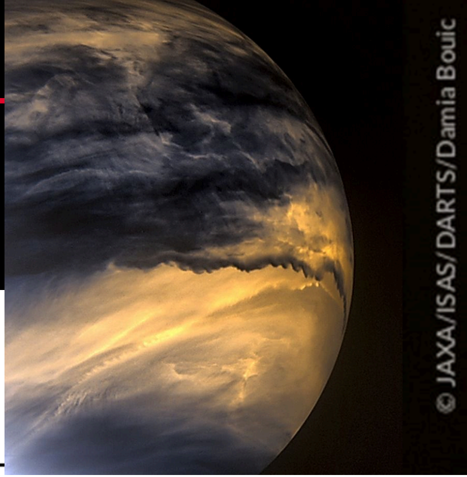
Chemistry-condensation cycles dominate environment

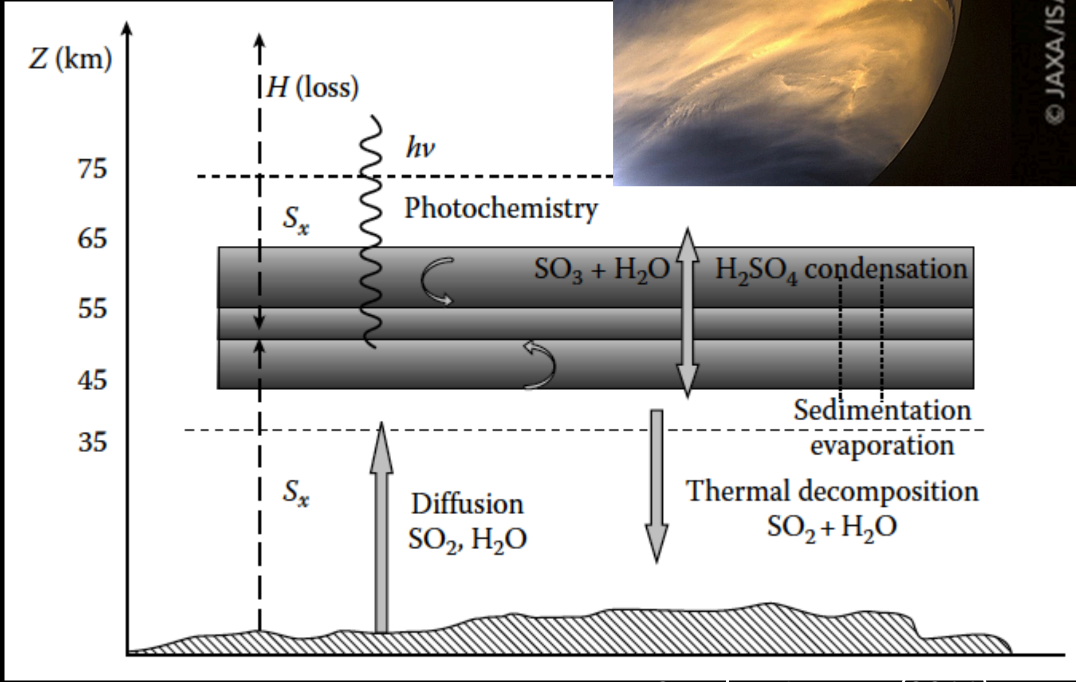




Chemistry and the Clouds of Venus

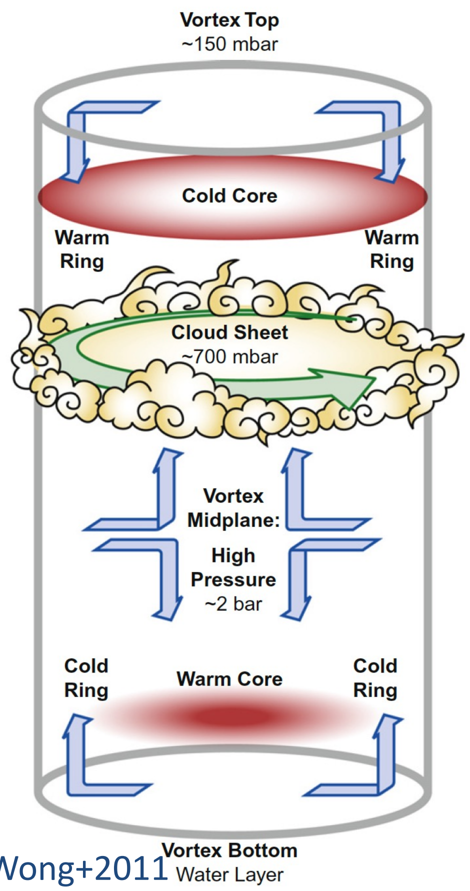
- Strong aqueous solution of **sulphuric acid H_2SO_4**:
  - SO_2 and SH_2 from the surface (volcanism?) react with dissociated O_2 to produce SO_3, which reacts with H_2O to form sulphuric acid droplets.
  - Rainout of the H_2SO_4 to the deep layers, evaporating before they hit the ground (**virga**).
- **Ultraviolet markings** in the cloud tops are from a secondary, unknown, variable constituent.



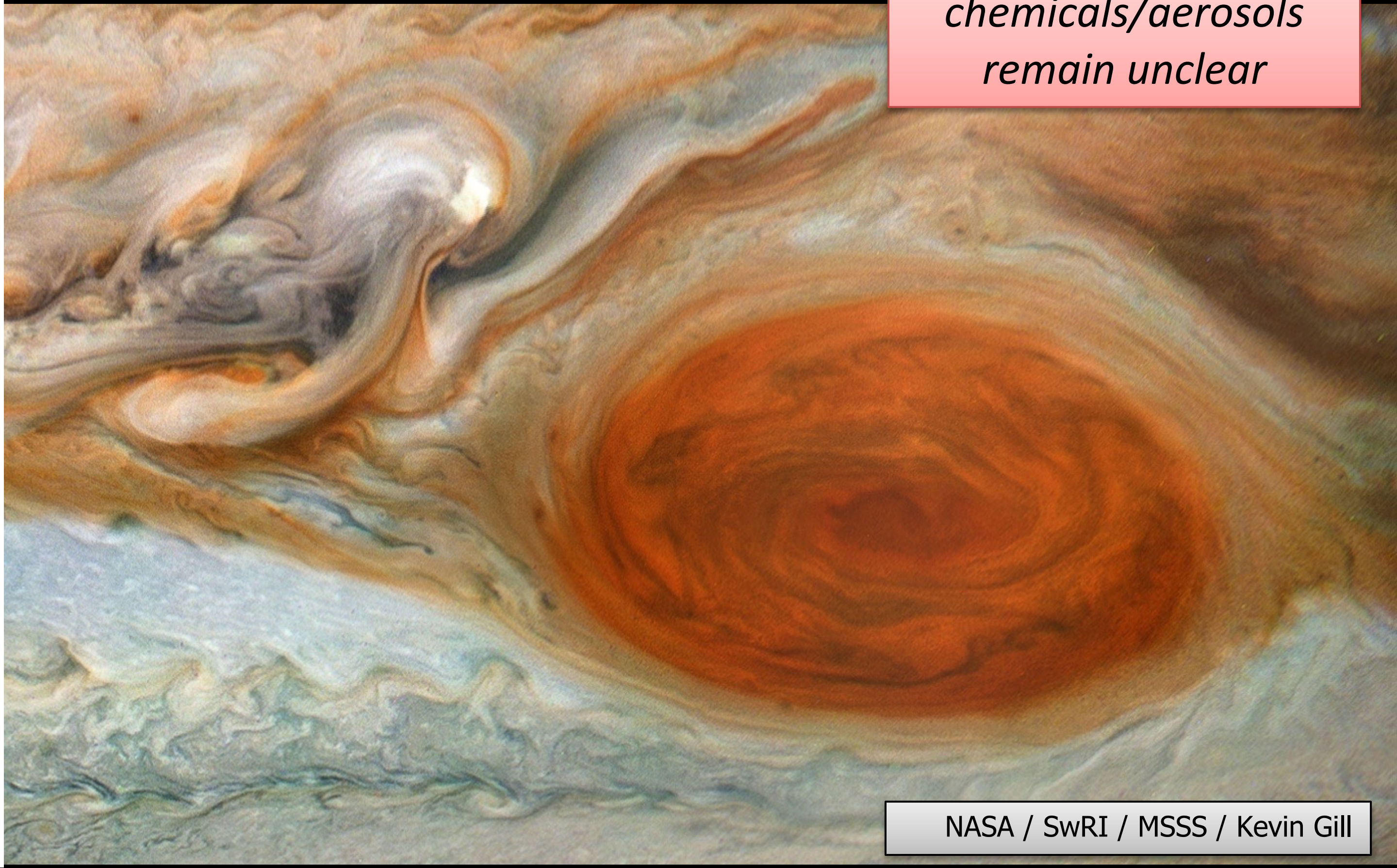


Sanchez-Lavega (2011)

Searching for Jupiter's Chromophore



Wong+2011

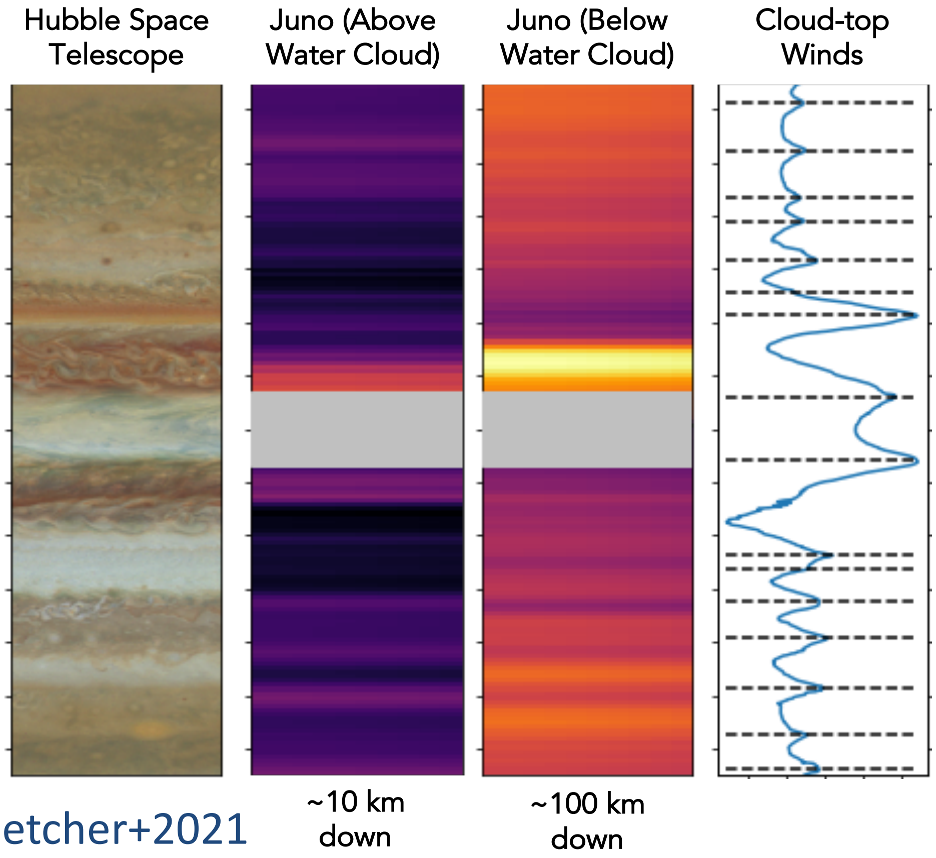


Identity of chemicals/aerosols remain unclear

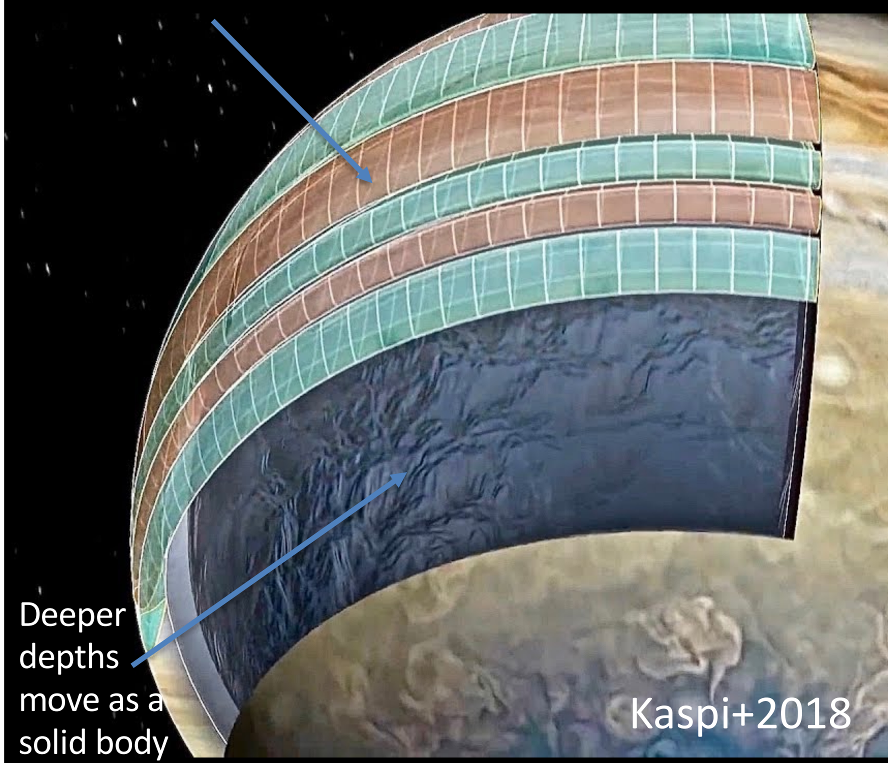
NASA / SwRI / MSSS / Kevin Gill

Atmospheric layering may be important

Environment and circulation changes as a function of depth



Fletcher+2021

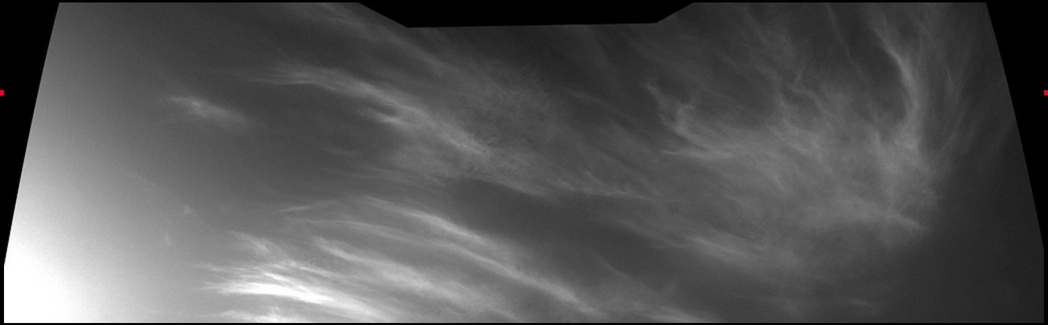


Summary So Far…

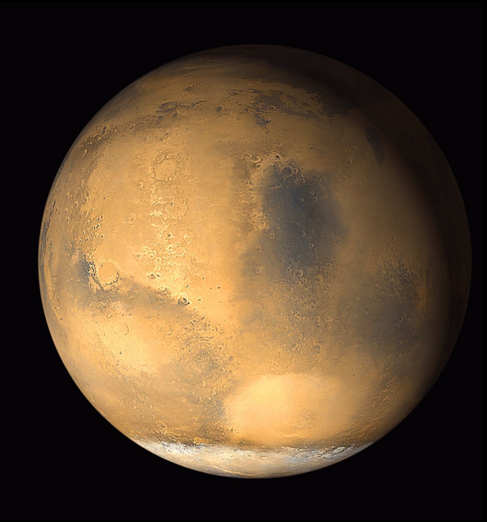
- **One condensate – very complex.**
  - Multiple condensates in mixed layers.
  - Latent heat & stabilizing effects.
- **ECCMs fail to reproduce observations:**
  - Volatiles not well mixed below clouds.
  - Exotic phases might be important.
  - Disequilibrium is everywhere.
  - CCNs needed to seed heterogeneous nucleation.
- **Spectral retrievals degenerate**
  - Broad spectral coverage needed.
  - Start from simplest model.
  - Pure ices are rarely seen.
- **Photochemistry is key:**
  - Chemicals coat clouds, serve as CCNs
  - Responsible for elusive chromophores.
- **Environment changes with altitude**

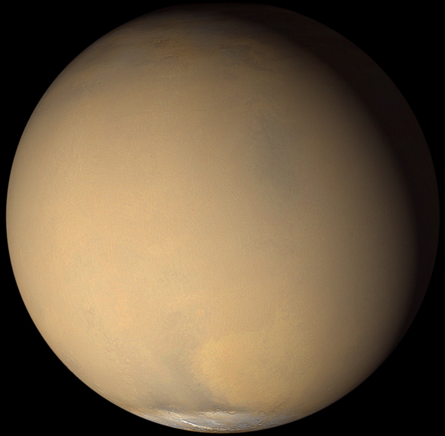
ALL THIS CHANGES WITH TIME

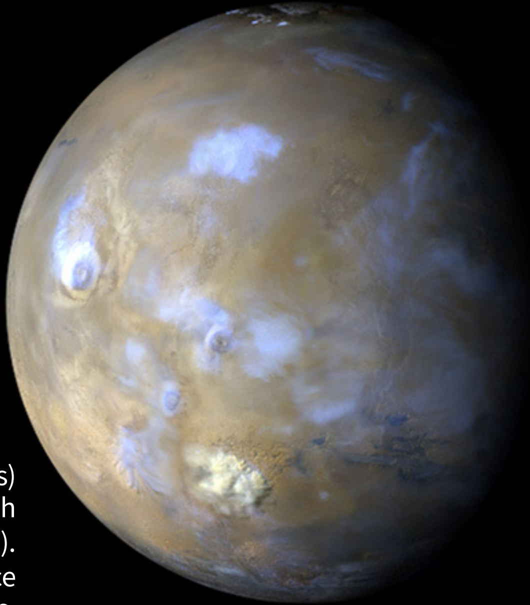
Clouds & Dust of Mars



- Three main seasonal cycles: water, CO_2 and dust.
- All three cycles are coupled.







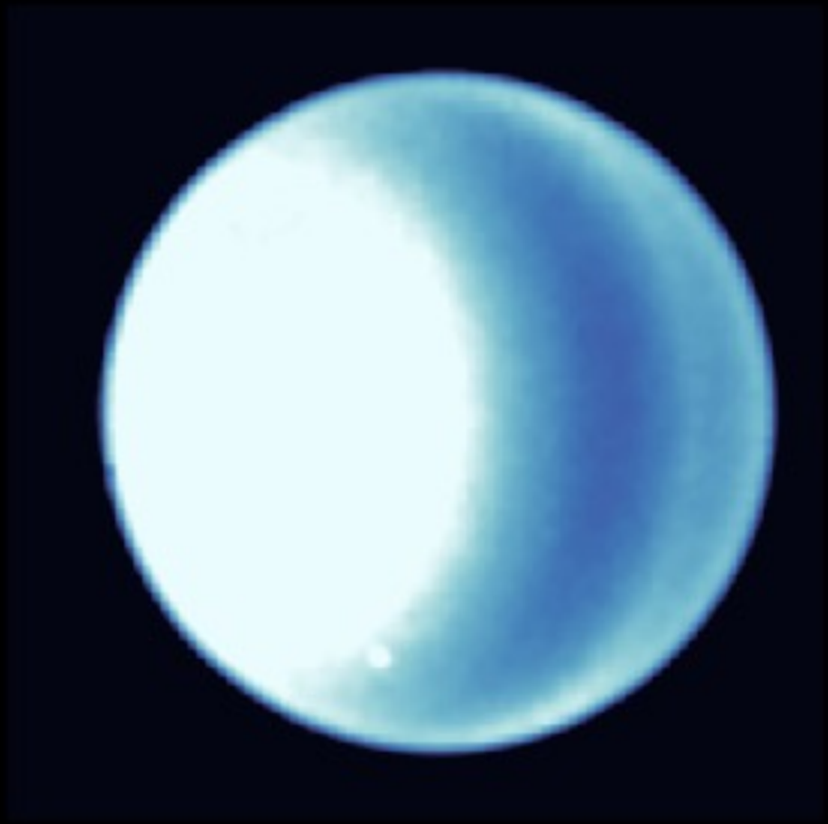
Visible clouds (bluish hazes) and dust storms (yellowish plume in lower centre). NASA/JPL-Caltech/Malin Space Science Systems.

Neptune: Clouds change from day-to-day

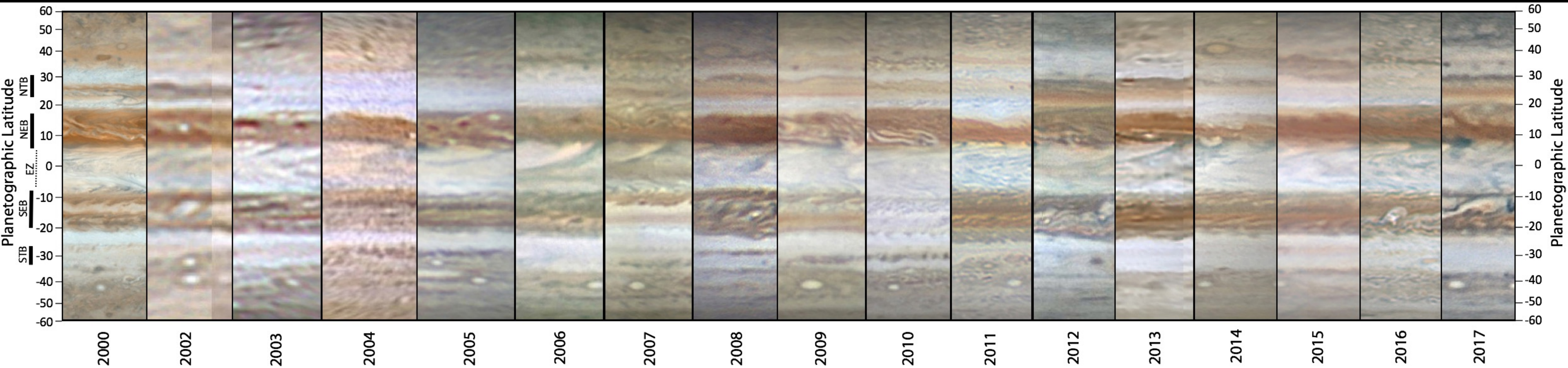
Uranus: Seasonal Polar hood of reflective aerosols

Saturn: Seasonal colour changes & annual storms

Jupite belt/zo

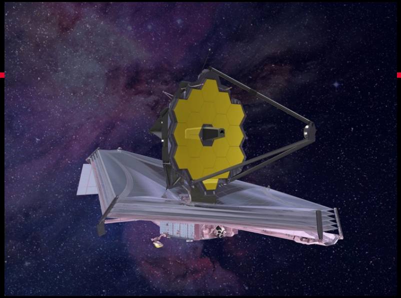


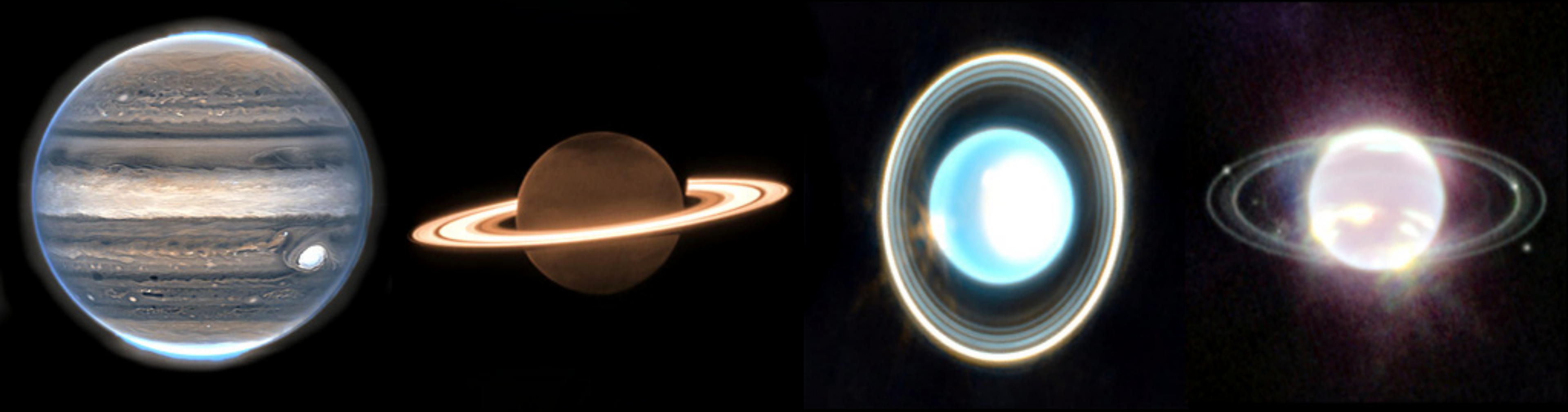
Searching for Climate Cycles – Jupiter's Bands



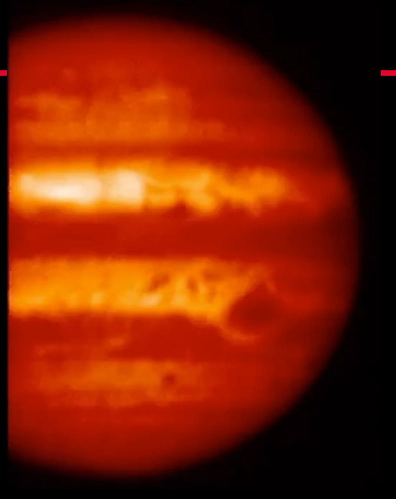
Fletcher (2017) arXiv:1708.05180

New Eye on the Solar System

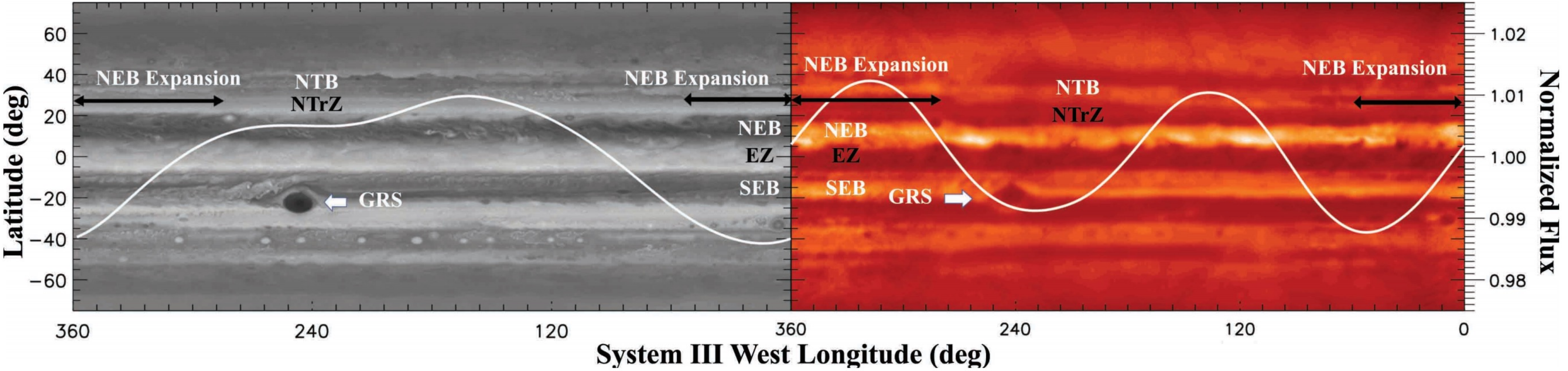




Rotational Variability from Changing Storms



- Ge et al. *Rotational Light Curves of Jupiter from UV to Mid-Infrared and Implications for Brown Dwarfs and Exoplanets (arXiv:1901.01323)*



The Challenge of Solar System Observations

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- **ECCMs fail to reproduce observations:**
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- **Photochemistry is key:**
  - Chemicals coat clouds, serve as CCNs
  - Responsible for elusive chromophores.
- **Environment changes with altitude**

- **Atmospheres are always changing:**
  - Colour changes
  - Sublimation/condensation changes.
  - Seasonal photochemistry seeding clouds.
  - Dust storms.
  - Natural cycles
  - Rotational variability

The Challenge of Solar System Observations

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

- T.S. Eliot
- From “Little Gidding,” Four Quartets (Gardners Books; Main edition, April 30, 2001) Originally published 1943.

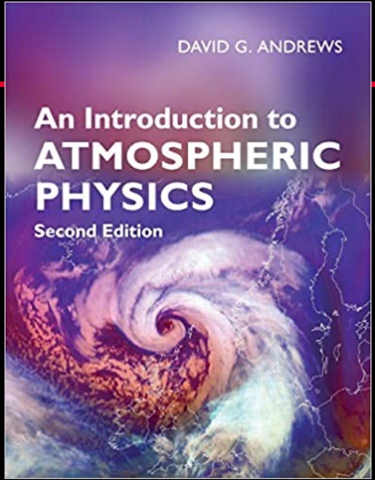
Supplementary Material

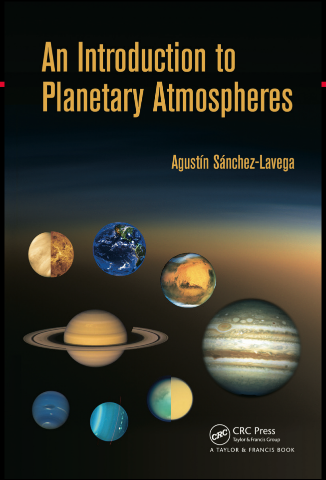
Recommended Reading

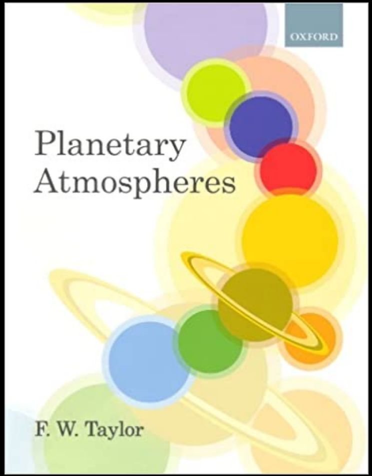
- **Specific Course Texts**
  - 'An Introduction to Atmospheric Physics' (2nd edition), D. G. Andrews (CUP, 2010), ISBN-13: 9780521693189
  - 'Planetary Atmospheres,' F.W. Taylor (OUP, 2010), ISBN: 978-0-19-954742-5
  - 'An Introduction to Planetary Atmospheres,' A. Sanchez-Lavega (CRC Press, 2011), ISBN-13: 978-1-4200-6732-3

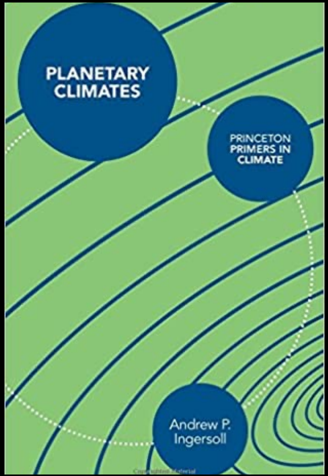
- **General Planetary Texts**
  - 'Planetary Sciences' (2nd edition), J. Lissauer & I. de Pater, (CUP, 2010).
  - 'Planetary Climates,' A.P. Ingersoll (Princeton University Press, 2013), ISBN: 978-0-691-14504-4

- **General Atmospheres Text:**
  - 'Atmospheric Science, An Introductory Survey', 2nd edition, J. M. Wallace and P. V. Hobbs (AP, 2006), ISBN-10: 012732951X

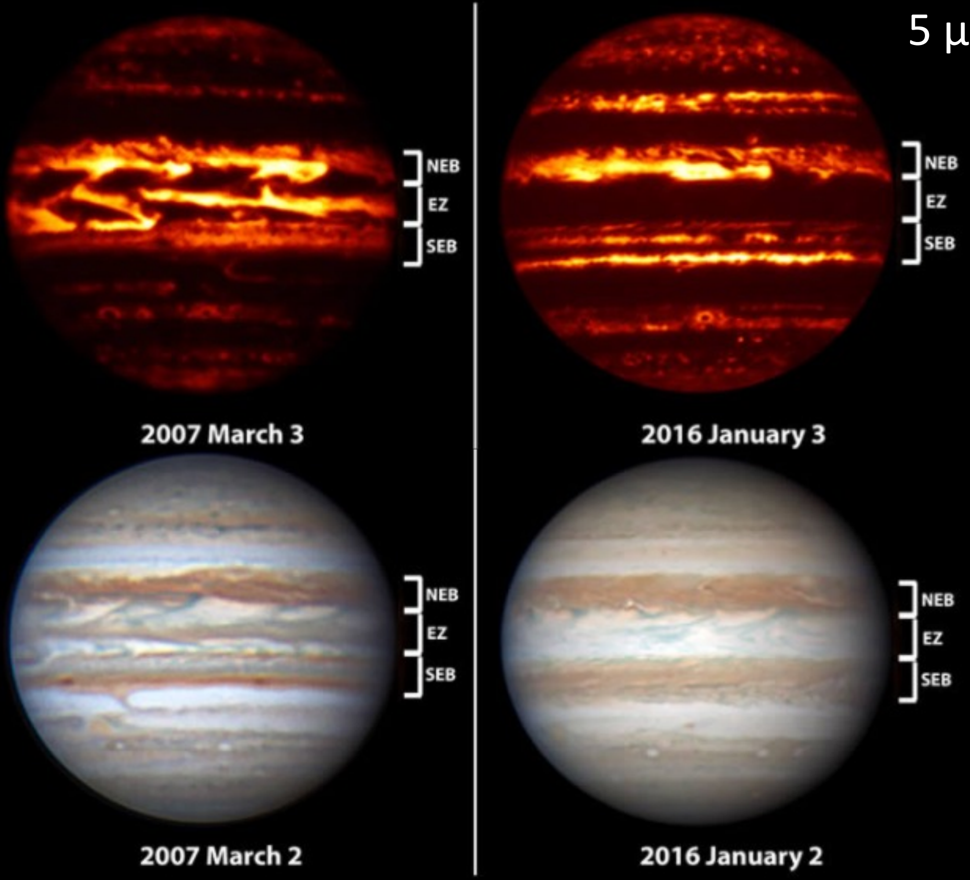






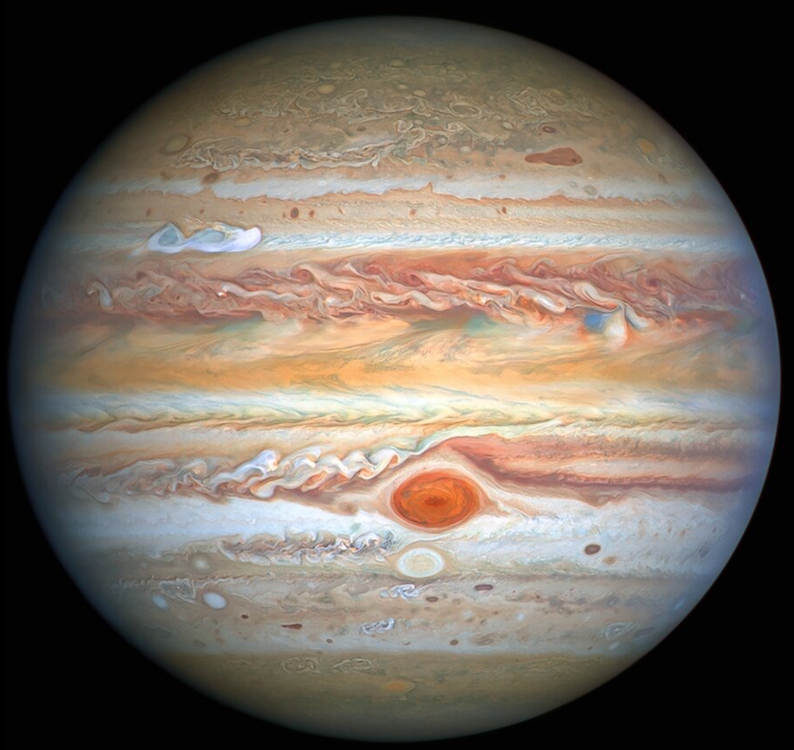


Equatorial Cloud Disturbance

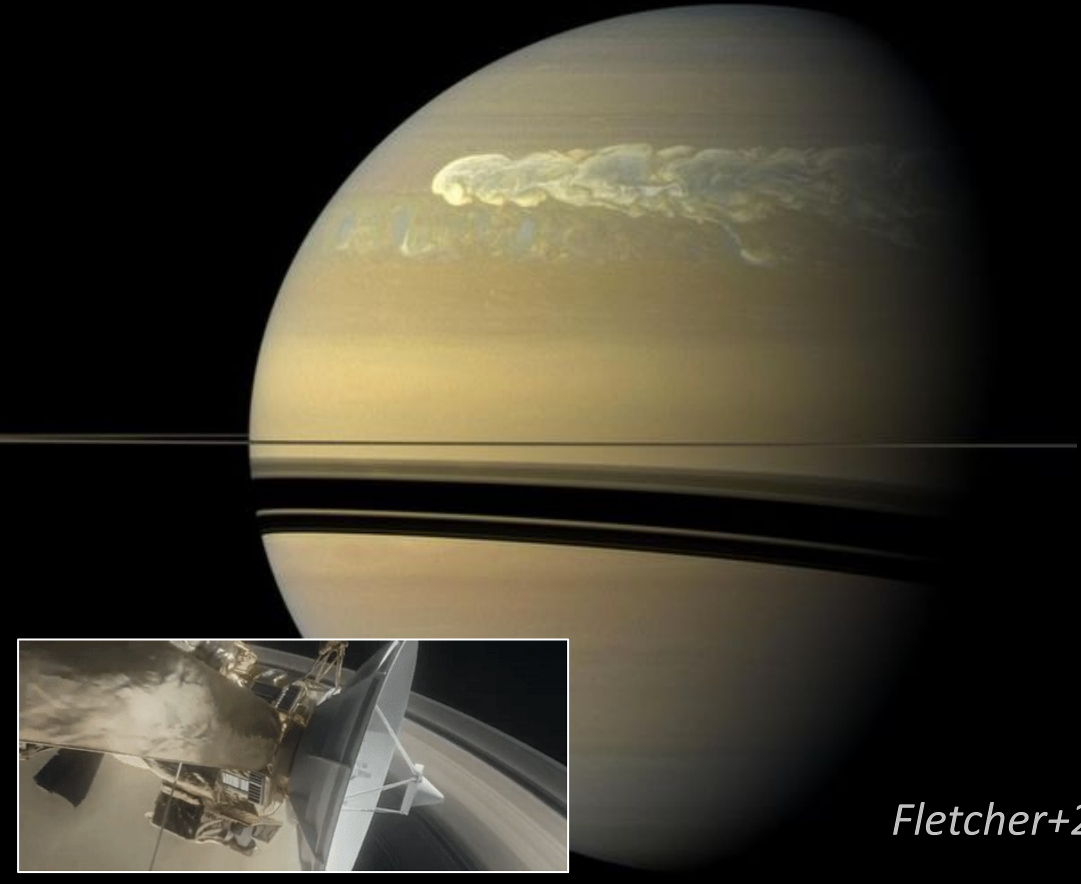


5 µm

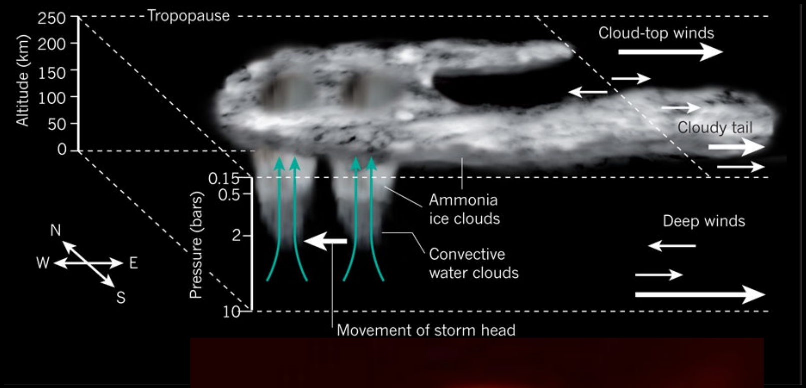
- Cloud-clearing events at the equator every 6-7 years – Antuñano+2018.



Saturn's Great Storms



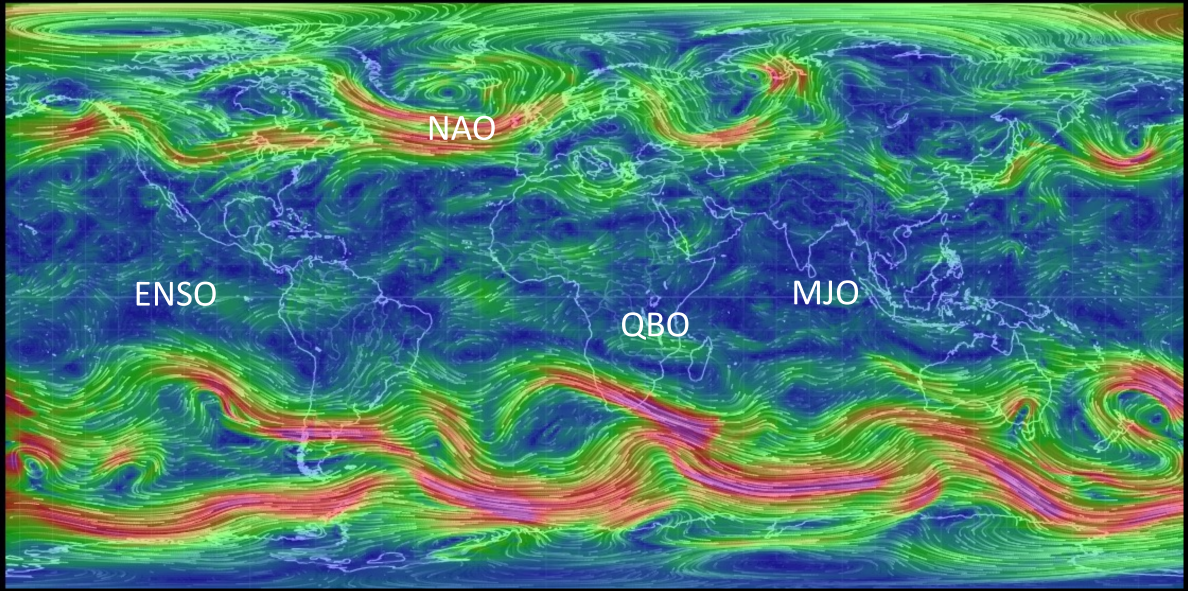
Fletcher+2012



VLT/VISIR 13 μm, July 24 2011

Natural Climate Cycles on Giants?

Earth's 500-mbar winds & oscillations

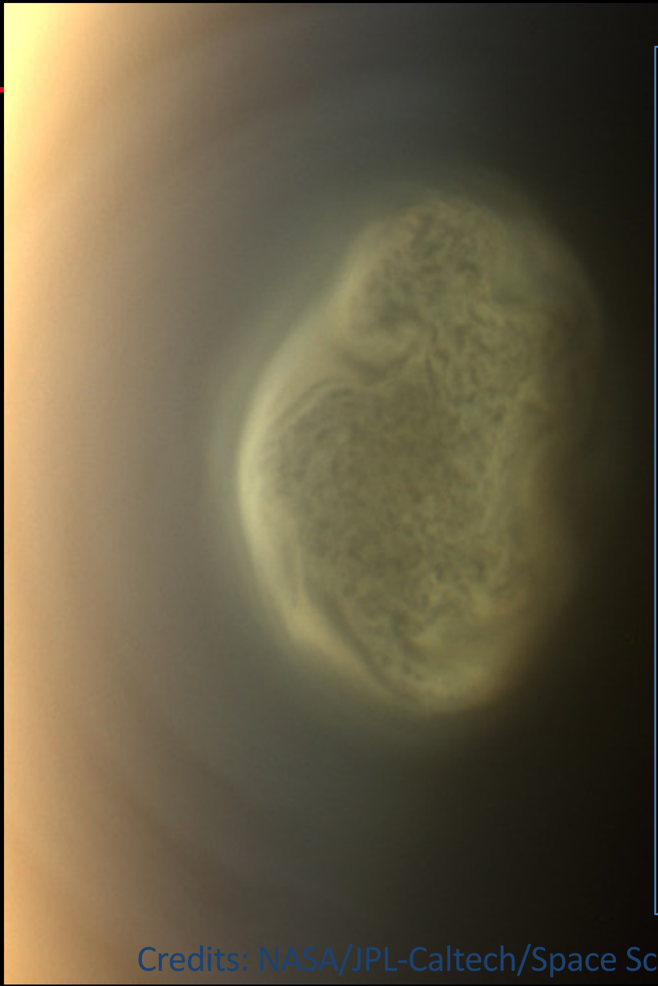
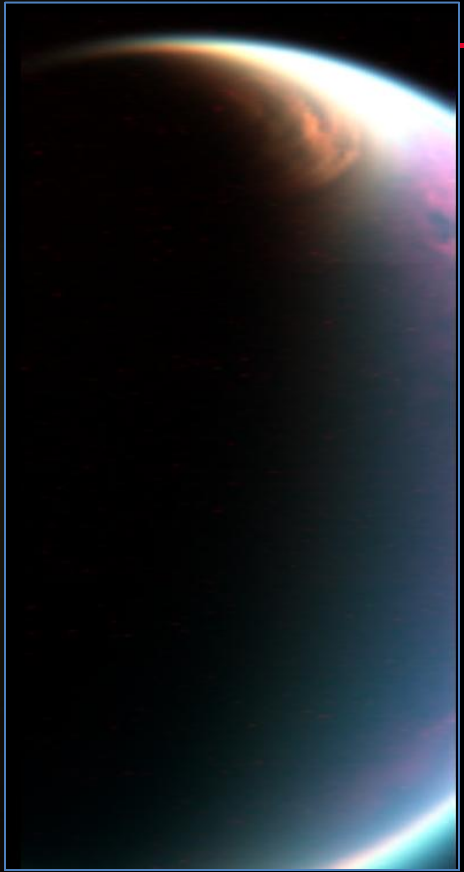


- *Convective patterns (e.g., Madden-Julian, MJO)*
- *Interannual patterns (e.g., El Nino, NAO)*
- *Wave-driven patterns (quasi-biennial oscillation, QBO).*

- Jupiter periodicity studies to date imply "something" controlling variations.
  - Deep interior waves?
  - Convective inhibition?
  - Coupling to magnetosphere?

Titan’s Polar Clouds

- In addition to methane cumulus & hydrocarbon haze strata, clouds of ethane and HCN have been observed at very cold temperatures, such as at the polar mesosphere.
- Frozen HCN ice at 125 K – very cold!

Credits: NASA/JPL-Caltech/Space Science Institute

Jupiter's Clouds (July 2022)

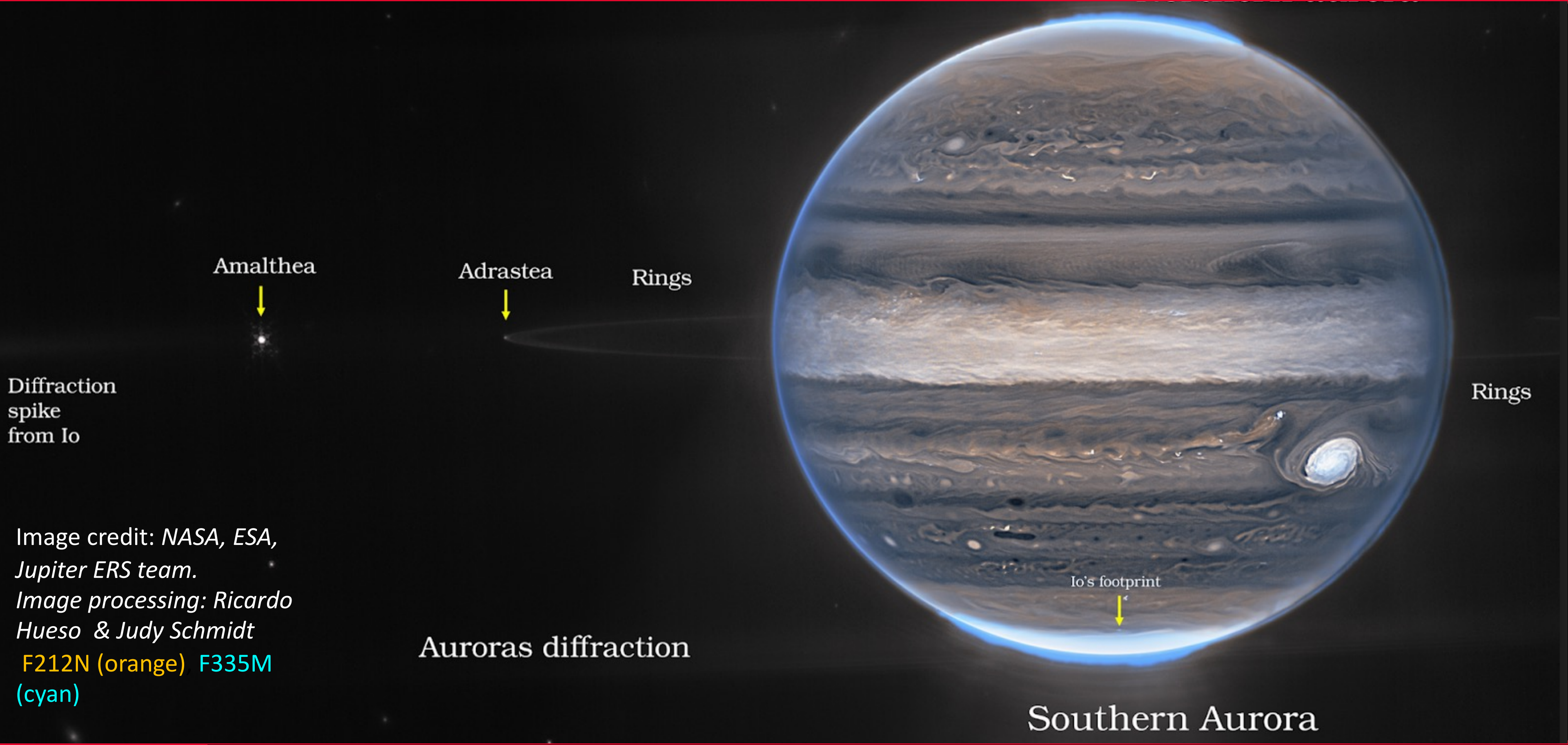
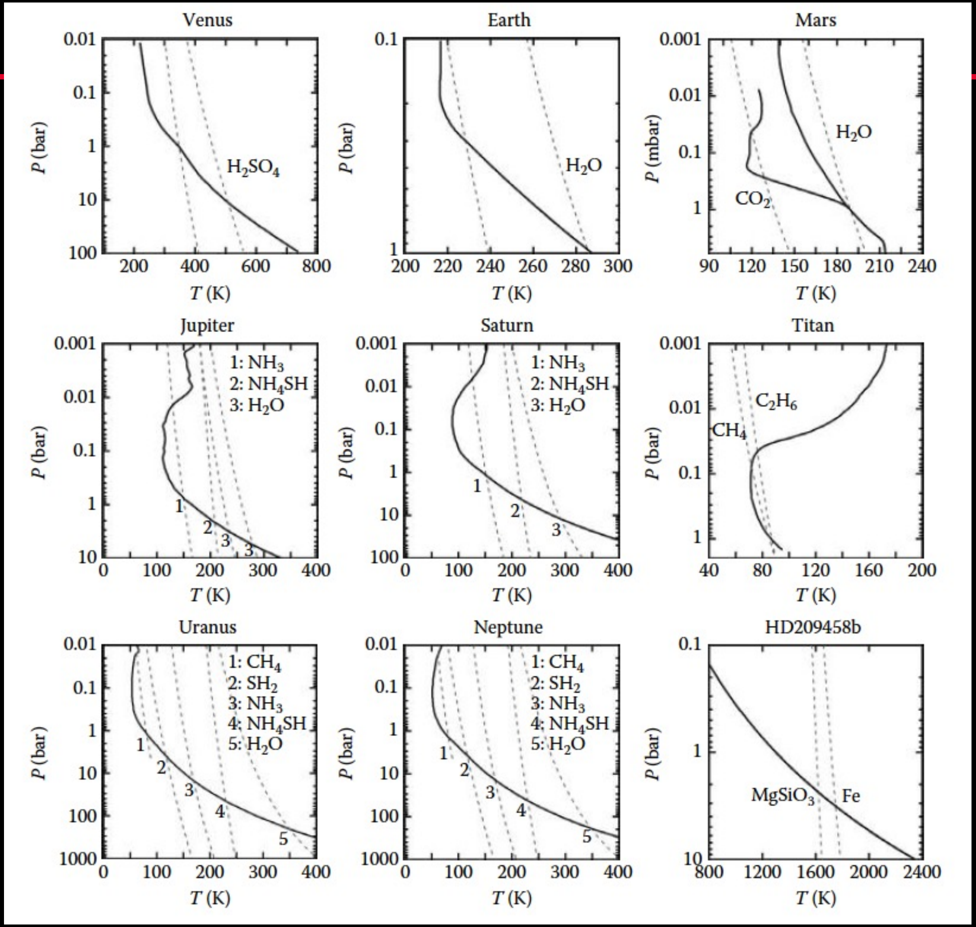


Image credit: *NASA, ESA, Jupiter ERS team. Image processing: Ricardo Hueso & Judy Schmidt*

F212N (orange) F335M (cyan)

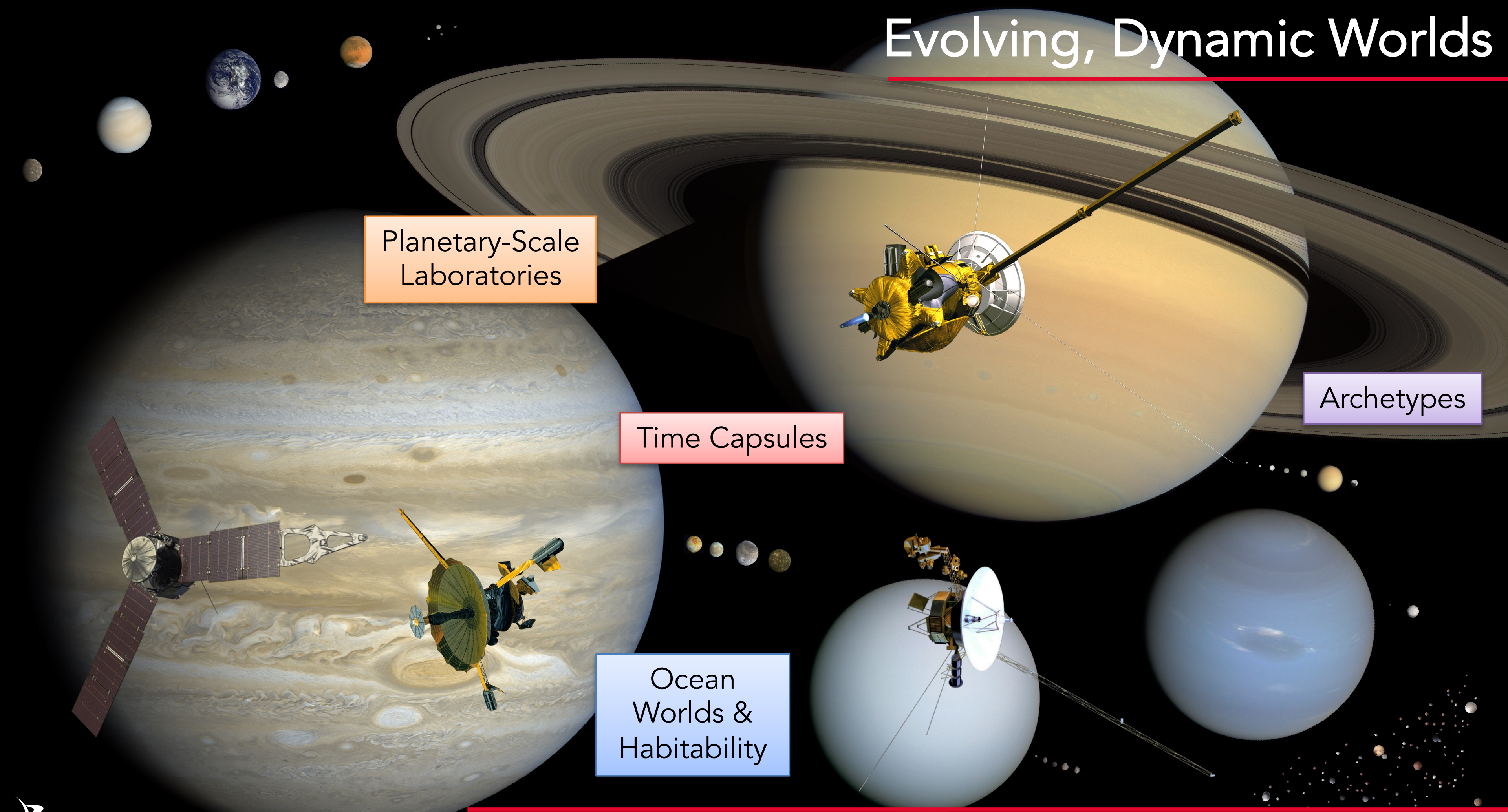
Cloud Layers

- Unlike Earth, where H_2O is the main cloud-forming species, other planets can have multiple layers of clouds as a function of temperature.
  - Convective processes can mix the strata.
- Despite the low mixing ratios of most condensables, they have a significant role in weather and climate processes.
- There are two cases where clouds come from chemistry:
  - Venus' H_2SO_4 clouds,
  - Giant planet NH_4SH clouds which form from reaction of NH_3 and H_2S.
- Finally, there are cases where hydrocarbons (from carbon photochemistry) and nitriles (from coupled carbon-nitrogen photochemistry) condense to form haze layers on Titan and the giant planets.



Sanchez-Lavega et al. (2004)

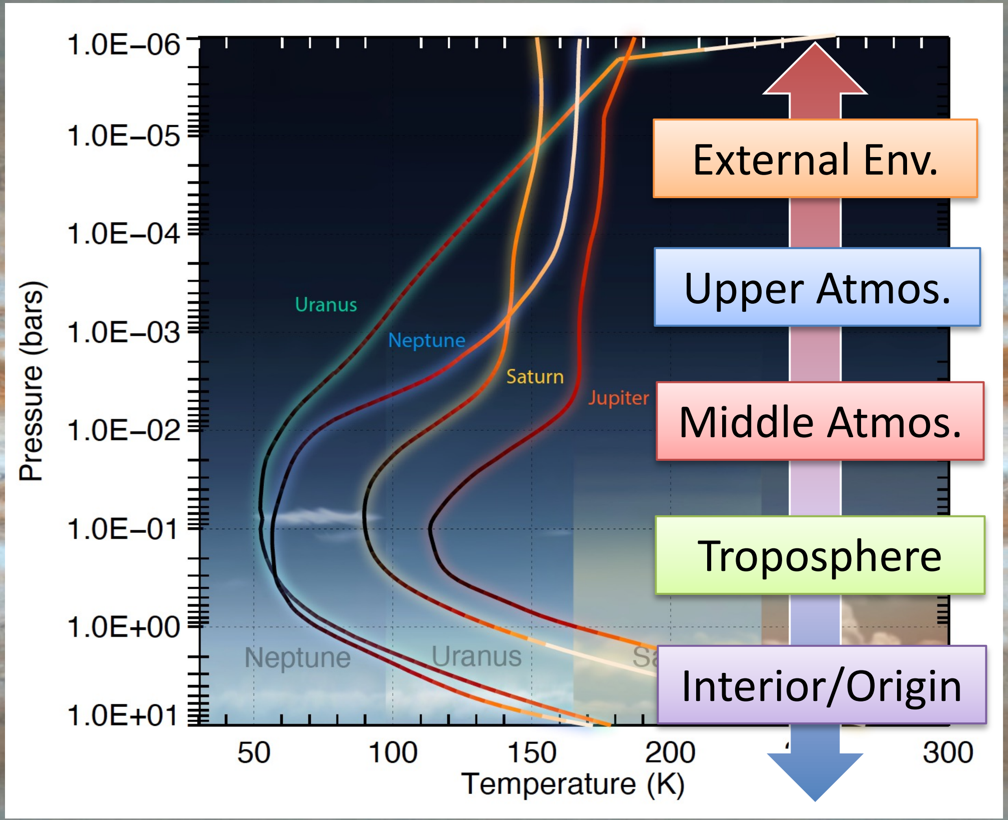
Evolving, Dynamic Worlds



Montage © 2011 Emily Lakdawalla, The Planetary Society. Image data courtesy NASA/JPL and JHUAPL/CIW.

Images from NASA/JPL & JHUAPL missions, processed by Bjorn Jonsson; Mattias Malmer; Ted Stryk; Gordan Ugarkovic; TNOs NASA, ESA, and A. Feild (STScI)

Giant Planet Vertical Structure

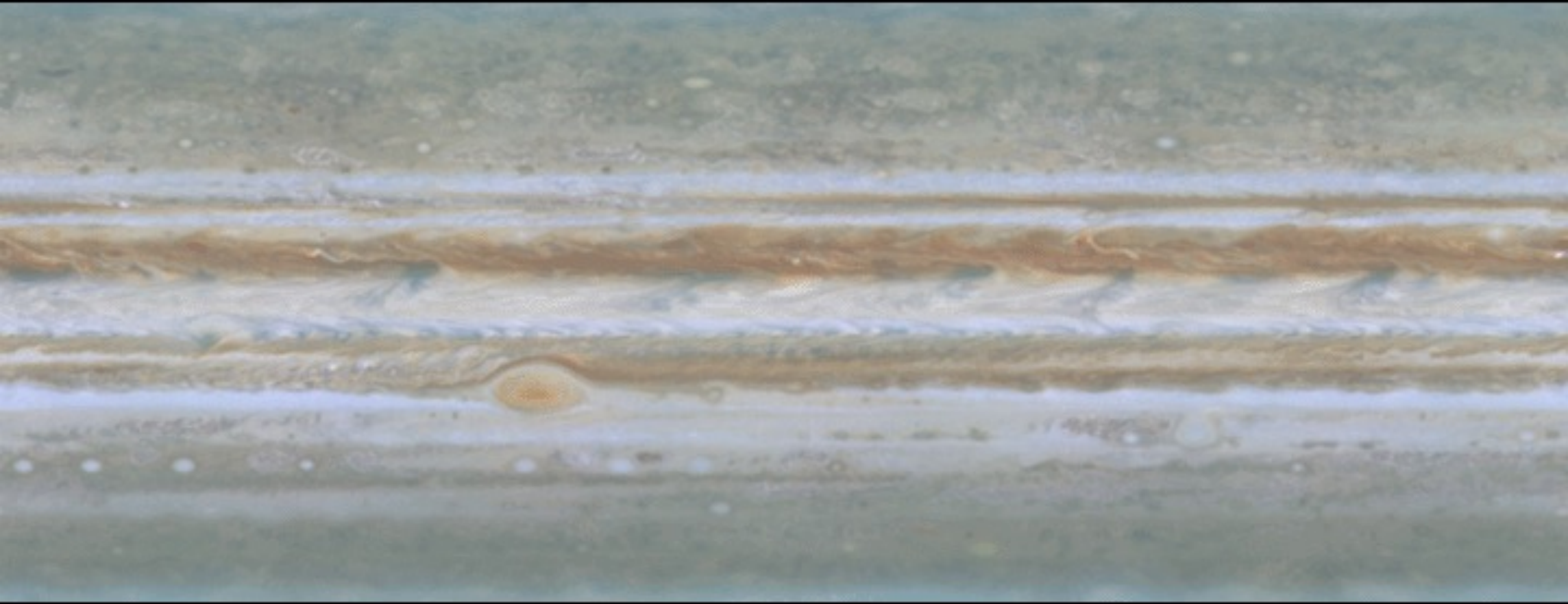


Photochemistry RADIATIVE LAYERS

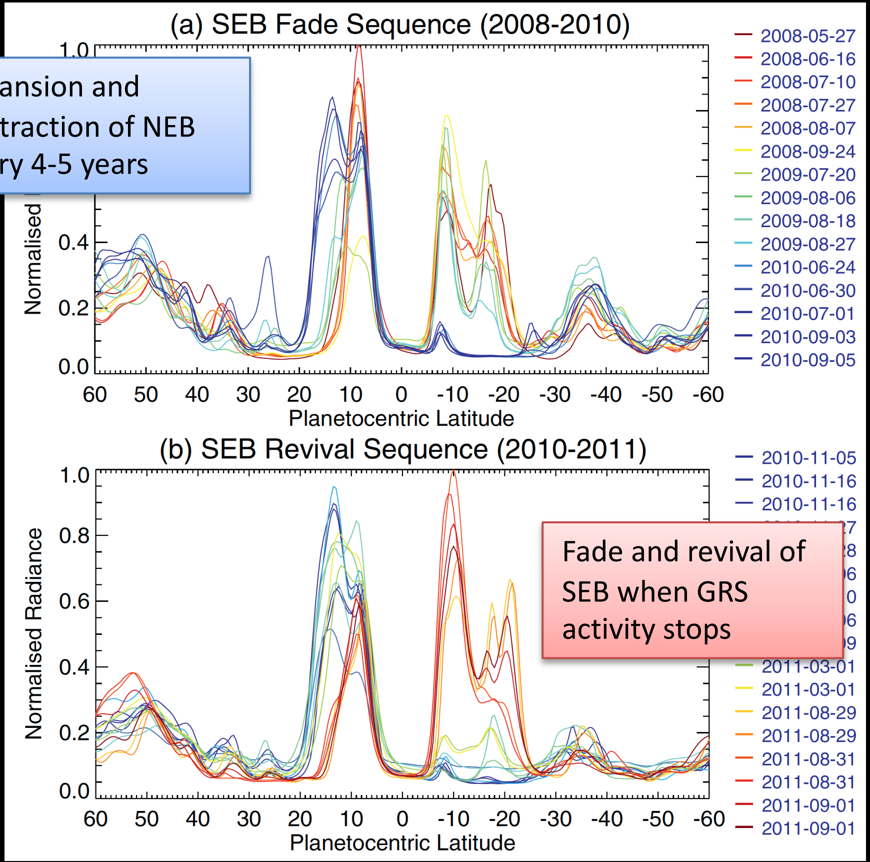
Condensation chemistry WEATHER LAYER

Thermochemistry DRY/DEEP LAYERS

The Winds of Giants

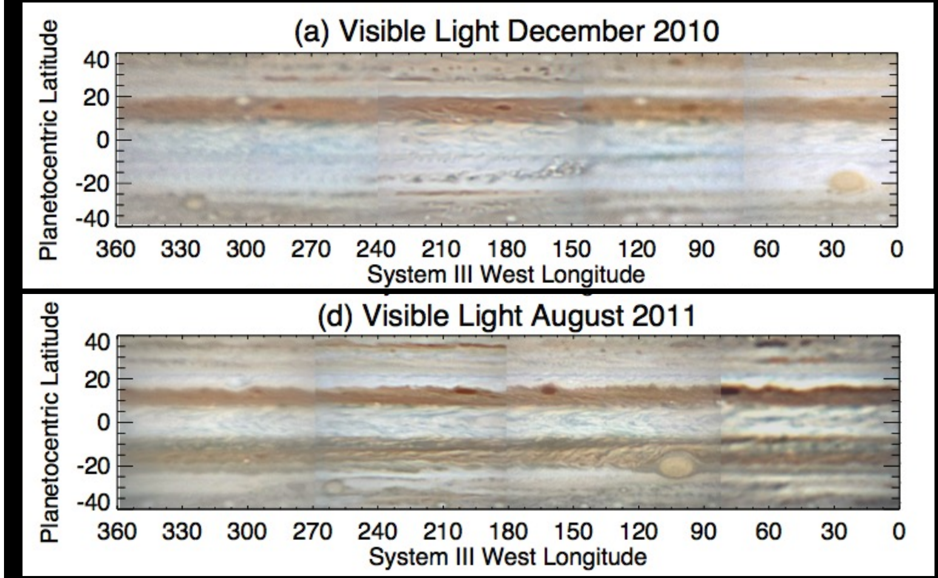


Tropospheric Cycles in Equatorial Belts



Expansion and contraction of NEB every 4-5 years

Fade and revival of SEB when GRS activity stops



- Changes to the circulation cells outlined previously?

Saturn’s Polar Storms