Lessons Learned from Solar System Exploration
(Defying Expectations since the 1960s)
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.”
Earth: One Condensable – Huge Complexity

- Cirrus (Ci)
- Cirrocumulus (Cc)
- Cirrostratus (Cs)
- Altostratus (As)
- Altocumulus (Ac)
- Stratocumulus (Sc)
- Cumulus (Cu)
- Cumulonimbus (Cb)
- Nimbostratus (Ns)
- Stratus (St)

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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.

Guillot+2020; Becker+2020
Disequilibrium is everywhere

Thermochemistry

Volatiles:
- CH₄
- NH₃, H₂S, H₂O

Photochemistry

Photochemicals:
- C₂H₂
- C₂H₆
- C₃Hₓ, C₄Hₓ...

Exogenic:
- H₂O
- CO₂
- CO

Condensation chemistry

Disequilibrium chemistry

- PH₃
- AsH₃, GeH₄, CO
- Para-H₂
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.
Irwin+2022

- Photochemical haze in stratosphere.
- $\text{CH}_4$ stability barrier at condensation level
- Rapid methane condensation (snow).
- $\text{CH}_4$ 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.

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Sromovsky+2013

Baines+2002
Chemical Masking & Photochemical Hazes?

Chemistry-condensation cycles dominate environment
Chemistry and the Clouds of Venus

• Strong aqueous solution of **sulphuric acid** $\text{H}_2\text{SO}_4$:
  – $\text{SO}_2$ and $\text{SH}_2$ from the surface (volcanism?) react with dissociated $\text{O}_2$ to produce $\text{SO}_3$, which reacts with $\text{H}_2\text{O}$ to form sulphuric acid droplets.
  – Rainout of the $\text{H}_2\text{SO}_4$ 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

Identity of chemicals/aerosols remain unclear

Wong+2011

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Atmospheric layering may be important.

<table>
<thead>
<tr>
<th>Hubble Space Telescope</th>
<th>Juno (Above Water Cloud)</th>
<th>Juno (Below Water Cloud)</th>
<th>Cloud-top Winds</th>
</tr>
</thead>
</table>

Cylinders of wind 3000 km deep.

Deeper depths move as a solid body.

Kaspi+2018

Fletcher+2021

Environment and circulation changes as a function of depth.
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

Jupiter: Cycles of belt/zone variability
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

- One condensate – very complex.
  - Multiple condensates in mixed layers.
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- ECCMs fail to reproduce observations:
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- Photochemistry is key:
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- Atmospheres are always changing:
  - Colour changes
  - Sublimation/condensation changes.
  - Seasonal photochemistry seeding clouds.
  - Dust storms.
  - Natural cycles
  - Rotational variability

- Environment changes with altitude
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

• General Planetary Texts

• General Atmospheres Text:
Equatorial Cloud Disturbance

- 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

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

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

Diffraction spike from Io

Auroras diffraction

Southern Aurora

Amalthea

Adrastea

Rings

Io’s footprint
Cloud Layers

- Unlike Earth, where $\text{H}_2\text{O}$ 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’ $\text{H}_2\text{SO}_4$ clouds,
  - Giant planet $\text{NH}_4\text{SH}$ clouds which form from reaction of $\text{NH}_3$ and $\text{H}_2\text{S}$.
- 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

Planetary-Scale Laboratories

Time Capsules

Ocean Worlds & Habitability

Archetypes

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

- **Giant Planets**:
  - Uranus
  - Neptune
  - Saturn
  - Jupiter

- **Layers**:
  - **Upper Atmos.**
  - **Middle Atmos.**
  - **Troposphere**
  - **Interior/Origin**

- **Chemistry**:
  - **Photochemistry**
  - **Condensation chemistry**
  - **Thermochemistry**

- **Pressures** (bars):
  - 1.0E-06
  - 1.0E-05
  - 1.0E-04
  - 1.0E-03
  - 1.0E-02
  - 1.0E-01
  - 1.0E+00

- **Temperatures** (K):
  - 50
  - 100
  - 150
  - 200
  - 300

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The Winds of Giants
Tropospheric Cycles in Equatorial Belts

- Changes to the circulation cells outlined previously?
  - Expansion and contraction of NEB every 4-5 years
  - Fade and revival of SEB when GRS activity stops

(a) SEB Fade Sequence (2008-2010)
(b) SEB Revival Sequence (2010-2011)

• Changes to the circulation cells outlined previously?
Saturn’s Polar Storms