Overview of Solar System Planet Atmospheres

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Today’s Outline

- Origins
- Giant planets
- Small bodies
- Terrestrial planets
- Conclusions
Atmospheres of the Solar System

• Giant planets
  – Primary atmospheres (H₂, He, CH₄…)
  – Little evolution (no surface, little escape)

• Terrestrial planets (Earth, Venus, Mars, Titan)
  – Secondary atmospheres (CO₂ / N₂, N₂ / O₂, N₂ / CH₄)
  – Outgassed and strongly evolved (escape, surface interaction)

• Tenuous atmospheres (Pluto, Triton, Io, Enceladus)
  – In equilibrium with surface ices or internal sources

• Exospheres (Mercury, Moon, other Galilean satellites)
  – Solar flux or solar wind action on surfaces
Table 1.3 List of three most abundant gases in planetary atmospheres. Mixing ratios are given in parenthesis. All compositions refer to the surface or 1 bar.

<table>
<thead>
<tr>
<th>Planet</th>
<th>H₂ (ppm)</th>
<th>He (ppm)</th>
<th>CH₄ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter</td>
<td>0.93</td>
<td>0.07</td>
<td>3 x 10⁻³</td>
</tr>
<tr>
<td>Saturn</td>
<td>0.96</td>
<td>0.03</td>
<td>4.5 x 10⁻³</td>
</tr>
<tr>
<td>Uranus</td>
<td>0.82</td>
<td>0.15</td>
<td>2.3 x 10⁻²</td>
</tr>
<tr>
<td>Neptune</td>
<td>0.80</td>
<td>0.19</td>
<td>1 - 2 x 10⁻²</td>
</tr>
<tr>
<td>Titan</td>
<td>0.95 - 0.97</td>
<td>3 x 10⁻²</td>
<td>2 x 10⁻³</td>
</tr>
<tr>
<td>Triton</td>
<td>0.99</td>
<td>2 x 10⁻⁴</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Pluto</td>
<td>?</td>
<td>?</td>
<td>CO ?</td>
</tr>
<tr>
<td>Io</td>
<td>SO₂ (0.98)</td>
<td>SO (0.05)</td>
<td>O (0.01)</td>
</tr>
<tr>
<td>Mars</td>
<td>CO₂ (0.96)</td>
<td>N₂ (2.7 x 10⁻²)</td>
<td>Ar (1.6 x 10⁻²)</td>
</tr>
<tr>
<td>Venus</td>
<td>CO₂ (0.96)</td>
<td>N₂ (3.5 x 10⁻²)</td>
<td>SO₂ (1.5 x 10⁻⁴)</td>
</tr>
<tr>
<td>Earth</td>
<td>N₂ (0.78)</td>
<td>O₂ (0.21)</td>
<td>Ar (9.3 x 10⁻³)</td>
</tr>
</tbody>
</table>
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At the relevant $T$, $NH_3$ is the thermodynamical equilibrium form of $N$ \(\rightarrow\) In principle $NH_3 / H_2$ gives the $N/H$ ratio

… but $PH_3$ is NOT the equilibrium form of $P$

Competition between chemical destruction and vertical convective transport

Quench level: where $t_{\text{chem}} \sim t_{\text{dyn}}$

Occurs at $T \sim 1200$ K for phosphine

\(\rightarrow\) Observed $PH_3$ abundance still gives $P/H$ ratio!
Comets are sources for atmospheres

16-23 July 1994

HST Noll et al. 1995

JCMT 15-m
Moreno et al. 2003
Methane photochemistry in Giant Planets (a recent view…)

Moses et al. 2000 (Saturn)
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Spectroscopy from recent space missions: the 3-D view

Study of couplings between chemistry and dynamics

... but no new detections (except many isotopes)...

Titan
Cassini CIRS/(R=0.5 cm⁻¹)
In situ measurements: the chemical complexity of Titan’s upper atmosphere from Cassini / INMS

Molecules detected on Titan by INMS (≈1100 km)

<table>
<thead>
<tr>
<th>&gt; 10 ppm</th>
<th>&lt; 10 ppm</th>
<th>≈ ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{C}_2\text{H}_2$</td>
<td>$\text{C}_3\text{H}_4$</td>
<td>$\text{C}_6\text{H}_2$</td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_4$</td>
<td>$\text{C}_3\text{H}_8$</td>
<td>$\text{CH}_3\text{C}_6\text{H}$</td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_6$</td>
<td>$\text{C}_6\text{H}_6$</td>
<td>$\text{C}_8\text{H}_2$</td>
</tr>
<tr>
<td>$\text{C}_4\text{H}_2$</td>
<td>$\text{CH}_3\text{C}_6\text{H}_5$</td>
<td>$\text{CH}_3\text{C}_3\text{N}$</td>
</tr>
<tr>
<td>HCN</td>
<td>CH$_3$CN</td>
<td>HC$_5$N</td>
</tr>
<tr>
<td>C$_2$H$_3$CN</td>
<td>C$_2$H$_5$CN</td>
<td>CH$_3$C$_3$N</td>
</tr>
<tr>
<td>HC$_3$N</td>
<td>C$_2$N$_2$</td>
<td>C$_5$H$_5$N</td>
</tr>
<tr>
<td>CH$_2$NH</td>
<td>NH$_3$</td>
<td>C$_6$H$_7$N</td>
</tr>
</tbody>
</table>

Neutral mode, Ion mode, Neutral + Ion mode, Tentative identification
In situ measurements: methane profile and meteorology in Titan’s atmosphere from Huygens

Methane drizzle on Titan
(Tokano et al. 2006)
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\[
\left( \frac{D}{H} \right)_{Mars} = 5 \times \left( \frac{D}{H} \right)_{Earth}
\]
\[
\frac{D}{H}(t) = \frac{D}{H}(0) \left( \frac{H(0)}{H(t)} \right)^{1-f}
\]
FIG. 1. Schematic diagram of physical processes included in the coupled chemical–aerosol microphysical model.

[Friedson et al., Icarus, 2002]
The uppermost clouds form a curtain and by day reflect sunlight back to dazzle us. By night, however, we become voyeurs able to peep into the backlit room behind.

D. Allen, Icarus, 1987
Mars: discovery of atmospheric water in 1963

Detection of H$_2$O on Mars (Spinrad et al. 1963) at 0.82 micron:

“Watershed” discovery
Mars’ atmosphere: basic chemistry

* Detection of CO (1968)
* Detection of O\(_3\) (1971), and O\(_2\) (1972)

*CO\(_2\) + \(h\nu\) \(\rightarrow\) CO + O
*O + O + M \(\rightarrow\) O\(_2\)
*O\(_2\) + O + M \(\rightarrow\) O\(_3\)
*H\(_2\)O + \(h\nu\) \(\rightarrow\) OH + H
*CO + OH \(\rightarrow\) CO\(_2\) + H
(stability of atmosphere)
*OH \(\rightarrow\) HO\(_2\) \(\rightarrow\) H\(_2\)O\(_2\)
(not detected before 2005)

* Detection of O\(_2\) 1.27 emission in 1976
\(\rightarrow\) tracer of ozone (and not vice versa!)

\[O_3 + h\nu \rightarrow O(^1D) + O_2(a^1\Delta_g)\]
\(220 \text{ nm} < \lambda < 320 \text{ nm}\)

excited state

Photon emission

\[O_2(a^1\Delta_g) \rightarrow O_2(X^3\Sigma_g^+) + h\nu\]
\(\tau \sim 3850 \text{ s}\)

Quenching by collisions with CO\(_2\)

\[O_2(a^1\Delta_g) + CO_2 \rightarrow O_2(X^3\Sigma_g^+) + CO_2\]

O\(_2\) emission at 1.27 \(\mu\)m
\(k \sim 10^{-20} \text{ cm}^3 \text{ s}^{-1}\)
Quenching factor

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Noxon et al. 1976
Conclusions

A fundamental understanding of chemistry in planets has been achieved

Common photochemistry: hundreds of molecules, thousands of reactions

Similar Processes: Catalytic cycles, evolution, hydrodynamic escape, thermal inversion
Acknowledgements

• NASA and ESA

• Yung’s Group at Caltech

• Lellouch’s review 2008

• Meadows et al. 2008

• Yung and DeMore (1999) Book
Back-up slides