"The Planets"
Astro/EPS C12 (CCN 17045 or 32505)

Dr. Michael H. Wong

Astronomy Department
University of California at Berkeley
mikewong@astro.berkeley.edu
astro.berkeley.edu/~mikewong/C12.html

LEC: 2 LeConte TTh, 2:40–5:00pm
Office Hours: 419 Campbell Hall,
Mon 3–4 and Tue 5–6

HEAT TRANSPORT MECHANISMS

- radiation: heat carried by light
  - the Sun
  - greenhouse effect
- conduction: heat transported by contact
- advection: physically moving heat from one place to another
- convection: heat transported by buoyancy and motion
  - plate tectonics

CONVECTION

- heating --> buoyancy
- buoyancy --> motion, transport of heat

LARGE-SCALE CONVECTION

Sinking Air
Developing Cloud Fueled by Convection
Thermals Rising Upward

COLD AIR DESCENDING
HEATED AIR RISING
COLD AIR DESCENDING
**ANGULAR MOMENTUM**

- Angular momentum is rotational inertia.
- Angular momentum is a "conserved" quantity: it doesn't change unless a torque is applied.

\[ L = m \cdot v \cdot r \]

*Where:*
- \( L \) is the angular momentum.
- \( m \) is the mass of the object.
- \( v \) is the linear velocity.
- \( r \) is the distance from the center of rotation.

- For a point mass rotating around an axis, angular momentum is conserved.

**CORIOLIS EFFECT**

Conservation of angular momentum:
- Everything at the surface has angular momentum due to the Earth’s rotation.
- A "coriolis force" pushes to the right (N hemisphere) or left (S hemisphere) of any large-scale surface motion.
- Toilets are not large-scale.

**HADLEY CELL**

![Diagram of Hadley cell](image)

Large-scale convective heat transport by convection

**HADLEY CIRCULATION**

Involves several concepts:
- Convection
- Coriolis effect
- Equator-to-pole variation in sunlight intensity
HEAT EXCESS

- Giant planets typically radiate more heat than they receive from the Sun.
- Heat source: gravitational contraction.
- Saturn may also be differentiating by "helium raindrops".
- Uranus is the exception: it does not have a "heat excess," although similar-sized Neptune radiates 2.6 times as much heat as it receives from the Sun.

ATMOSPHERIC COMPOSITION

<table>
<thead>
<tr>
<th></th>
<th>Protosolar</th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>0.84</td>
<td>0.86</td>
<td>0.88</td>
<td>0.83</td>
<td>0.80</td>
</tr>
<tr>
<td>He</td>
<td>0.16</td>
<td>0.14</td>
<td>0.12</td>
<td>0.15</td>
<td>0.18</td>
</tr>
<tr>
<td>CH₄</td>
<td>4.6x10⁻⁴</td>
<td>2.0x10⁻³</td>
<td>4.9x10⁻³</td>
<td>0.018</td>
<td>0.02</td>
</tr>
<tr>
<td>H₂O</td>
<td>8.6x10⁻⁴</td>
<td>4.2x10⁻⁴</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>NH₃</td>
<td>1.1x10⁻⁴</td>
<td>5.7x10⁻⁴</td>
<td>6x10⁻⁴?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>H₂S</td>
<td>2.6x10⁻⁵</td>
<td>7.7x10⁻⁵</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Ne</td>
<td>1.3x10⁻⁴</td>
<td>2.0x10⁻⁵</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

*Units are volume ratios.

ATMOSPHERIC COMPOSITION

<table>
<thead>
<tr>
<th></th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>He</td>
<td>0.83</td>
<td>0.89</td>
<td>0.94</td>
<td>1.2</td>
</tr>
<tr>
<td>CH₄</td>
<td>4.4</td>
<td>9.7</td>
<td>39</td>
<td>43</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.49</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>NH₃</td>
<td>5.1</td>
<td>4.4?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>H₂S</td>
<td>3.0</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Ne</td>
<td>0.15</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

*Relative to protosolar values.
ATMOSPHERIC STRUCTURE

- where do clouds condense? depends on:
  - temperature
  - amount of cloud-forming gas

astronomyonline.com

CLOUDS

- Jupiter + Saturn
  - ammonia
  - something with sulfur
  - water
  - photochemical haze

- Titan
  - hydrocarbon hazes
  - methane?
  - ethane?

- Venus
  - sulfuric acid

- Earth
  - liquid water, water ice

- Mars
  - water ice, $\text{CO}_2$ ice

Jupiter: Great Red Spot, 4.8 $\mu$m
NASA Infrared Telescope Facility

1995 Feb. 13
1995 Feb. 27
1995 March 9
1995 April 5
1995 April 15
1995 May 24
1995 July 11
1995 July 26
1995 Sep. 5
1995 Sep. 17

Spencer, Orton, Beebe et al., IRTF website

Wong et al. (2006), from IRTF data
Keck Observatory
NIRC2 LGS-AO
Imke de Pater, Mike Wong, Al Conrad

Jupiter's Red Spots
M-band thermal IR
21 July 2006 UT

Orton et al. (1998), from IRTF data

SATURN STORMS

Saturn’s “Dragon Cloud”
URANUS (KECK)

ATMOSPHERIC BLURRING

ADAPTIVE OPTICS

NEPTUNE: KECK AO

Laser-guided adaptive optics at Lick Observatory
WEATHER ON NEPTUNE

- Cloud patterns and albedos (reflectivities) vary over time

STORMS

Jupiter’s Great Red Spot

Lightning

Galileo spacecraft
Lightning

Convective storms
- Cassini ISS images
- Red clouds are at $P > 2-5$ bar

Porco et al. (2003)