Substellar Atmospheres

PHY 688, Lecture 18
Mar 9, 2009
Outline

• Review of previous lecture
  – the Kepler mission launched successfully
    • results $P < 1$ month planets by September ‘09
  – giant planet interiors
  – comparison to brown dwarfs

• Substellar atmospheres
  – treatment of opacity, local thermal equilibrium
  – chemical species
  – assessment of models
Previously in PHY 688...
compared to brown dwarfs, the interiors of giant planets are:
- more strongly degenerate ($\theta \equiv \eta$ in this diagram)
- more strongly Coulomb-coupled
Radius vs. Mass: Comparison with Known Planets

- for polytropes
  \[ R \propto M^{3-n} \]
  \[ n = \frac{1-n}{3-n} \]

- \( n = 1.5 \) for brown dwarfs
- \( n = 0.5 - 1.0 \) for 0.1–1 \( M_{\text{Jup}} \) planets
- \((n = 0\): uniform density\)
- icy/rocky cores in Neptune, Uranus?

\( R \gtrsim M^{1-n} \)

\( \text{olivine } (\text{Mg,Fe})_2\text{SiO}_4 \) planet

\( \text{H}_2\text{O} \) planet

\( \text{HD}209458b \)
Solar System Giant Planets

• Accurate masses from observations of natural satellite motions:
  – Jupiter: \( M = 317.834 \, M_{\text{Earth}} \)
  – Saturn: \( M = 95.161 \, M_{\text{Earth}} \)
  – Uranus: \( M = 14.538 \, M_{\text{Earth}} \)
  – Neptune: \( M = 17.148 \, M_{\text{Earth}} \)

• Rapid rotation (~10 hrs for J+S, ~17 hrs for U+N) distorts gravitational field:
  – \( \frac{R_{\text{equatorial}}}{R_{\text{polar}}} = 1.02 \) (Neptune) to 1.11 (Saturn)
  – non-zero gravitational moments \( J_i \)

• \( J_i \) obtained from analysis of spacecraft trajectories during flybys
  – Pioneer 10+11, Voyager 1+2, Ulysses, Galileo, Cassini
  – axial moments of inertia substantially less than those for uniform-density spheres
  – indicate central dense regions: rocky cores (?)
A Brown Dwarf’s and Jupiter’s Interiors

0.05 $M_{\text{Sun}}$ brown dwarf

$P \approx 10^{11} \text{ bar}, T \approx 10^6 \text{ K}, \rho \approx 500 \text{ g/cc}$

$P \approx 5 \text{ bar}, T \approx 1000 \text{ K}, \rho \approx 10^{-4} \text{ g/cc}$

165–170 K, 100 kPa (1 bar)

6300–6800 K, 200 GPa

Metallic H

Molecular H$_2$ ($Y \approx 0.23$)

Ices + Rocks core ?

$15000–21000 \text{ K}, 4000 \text{ GPa}$

($4 \times 10^9 \text{ bar}$)

(Guillot 2006)
Solar System Giant Planet Interiors

- sizes of rocky cores in Jupiter and Saturn are very uncertain

- interior structure of Uranus and Neptune is even more uncertain

(Guillot 1999)
The Existence of a Rocky/Icy Core in Jupiter’s is Uncertain

- solutions for the two EOS’s are mutually inconsistent
- middle ground is possible

regardless:
- $M_{\text{core}} < 10 \ M_{\text{Earth}}$
  - < 3% by mass
- $M_{\text{core}}$ could be 0

(Guillot 2006)
Saturn’s Core Mass is Better Constrained

- EOS’s that are discontinuous or interpolated across PPT agree
- core mass is 6–17 $M_{\text{Earth}}$
  - 6–18% of total mass

$(\text{Guillot 2006})$
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The Atmosphere:
A Critical Boundary Condition

- In solving for interior structure:
  - Lane-Emden equation; polytropes
  - at surface assume: $P \sim 0$, $T_{\text{eff}} \sim 0$

- In solving for (sub)stellar evolution and MMSM:
  - frequency-independent Rosseland mean opacity $\kappa_R$

\[
L = 3.82 \times 10^{-5} L_\odot \left( \frac{10^9 \text{ yr}}{t} \right)^{1.297} \left( \frac{M}{0.05 M_\odot} \right)^{2.641} \left( \frac{\kappa_R}{10^{-2}} \right)^{0.35}.
\]

\[
M_{\text{MMSM}} = 0.0865 M_{\odot} \left( \frac{10^{-2} \text{ g cm}^{-2}}{\kappa_R} \right) \frac{I(\eta)}{I(\eta_{\text{min}})}.
\]

- "Grey" opacities:
  - adequate for early-type stars, stellar interiors
  - inadequate for molecule-rich M/L/T atmospheres
The Optical to IR SEDs of UCDs (Cushing et al. 2006; Marley & Leggett 2008)

(Cushing et al. 2006; Marley & Leggett 2008)
Opacity of M/L/T Dwarfs is Non-Grey

(Allard & Hausschildt 1995)
Neutral Atoms and Molecules Are Strong Wavelength-Dependent Absorbers

Electronic transitions (X-ray/UV/optical)

Ro-vibration (optical/infrared)

Continuum sources (optical/infrared/submm/radio)

Scattering (optical/infrared)

bound-free  free-free
From Lecture 3: Radiative Transfer

The optical depth $\tau_\lambda$ accounts for interaction between photospheric matter and radiation field.

Modifications to blackbody SED:
absorption from metals in the atmosphere

$$I(\lambda) = I_0(\lambda)e^{-\tau_\lambda}$$

$$d\tau_\lambda = \kappa_\lambda \rho \cos \theta \, ds$$

The total optical depth (total absorption) for a given species depends on the column density.
Non-Grey Opacities

• Exact interaction between radiation field and matter is complicated and often intractable
  – vast number of excitable atomic and molecular transitions

• Assume local thermodynamic equilibrium (LTE)
  – radiation and matter characterized by the same temperature $T$
  – gas: Maxwell-Boltzmann, radiation: Planck

\[
f(v) = 4\pi \left( \frac{m}{2\pi kT} \right)^{3/2} v^2 \exp \left[ -\frac{mv^2}{2kT} \right] \quad I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}.
\]
Non-Grey Opacities, LTE

• In LTE, level populations completely determined by $T$ from the **Boltzmann** and **Saha** equations

\[
\frac{N_i}{N} = \frac{g_i \exp (-E_i / kT)}{\sum_j g_j \exp (-E_j / kT)}
\]

\[
\frac{Z_i}{N_i} = \frac{Z_{i+1} Z_e}{N_{i+1} N_e}
\]

\[
Z_i = \sum_i g_i e^{-E_i / kT}
\]

• Need “only” find all important transitions in dominant atoms and molecules
  – also a formidable problem
  – H$_2$O alone has hundreds millions of lines(!)
Validity of the LTE Assumption

- depends on coupling of radiation with matter
Validity of LTE Assumption Depends on Fate of Excited Atom/Molecule

- **bound-bound case:**
  - if excited state is collisionally de-excited
    - photon energy is absorbed by the gas
    - absorption couples radiation to matter through collisions
    - **if absorption dominates opacity, LTE approximation is valid**
  - if excited state is radiatively de-excited
    - original photon is scattered; its energy radiated away
    - no collisions, weak dependence on temperature of matter
    - transitions have finite energy width; re-emission at a low absorption probability wavelength can lead to further decoupling of radiation and matter
    - **if scattering dominates opacity, LTE approximation is not valid**

- **bound-free and free-free (continuum) cases, Thomson, Rayleigh scattering**
  - unimportant at low $T$, high $P$
Most Important Species in EOS

- $\text{H}_2\text{O}$: $4 \times 10^7$ lines
- $\text{CH}_4$: $1.7 \times 10^7$ lines
- $\text{TiO}$: $1.5 \times 10^6$ lines
- CO: $10^5$ lines
- $\text{NH}_3$: $10^4$ lines

- **dust**
- **condensate clouds**

(Allard & Hauschildt 1995)
Chemical Abundances and Species

(Burrows et al. 2001)
Infrared Opacities at Late-L: Dominated by Molecules

(Burrows et al. 2001)
Alkali Opacities in the Visible at Late-L

(Burrows et al. 2001)
Optical to Near-IR Opacities, $[\text{Fe/H}] = 0.0$

$T_{\text{eff}} = 2800$ K, $\log g = 5.0$

(Allard & Hauschildt 1995)
Optical to Near-IR Opacities, \([\text{Fe/H}] = -2.5\)

\[ T_{\text{eff}} = 2800 \text{ K}, \log g = 5.0 \]
Solar Metallicity vs. Metal-Poor Spectra

- the depletion of metals changes the ingredients for atmospheric chemistry
- thin condensate clouds, strong metal hydrides, strong H$_2$O

(Burgasser et al. 2006)
Solar Metallicity vs. Metal-Poor Spectra

(Burgasser et al. 2006)
With Decreasing Metallicity

- double-metal species (e.g., TiO) disappear
- metal-hydrides survive preferentially
- H\(^-\) continuum dominant at <1.1 micron
- CIA H\(_2\) dominant over 1.1–4 micron
- deeper layers revealed
  - metal-hydrides
  - pressure-broadened atomic absorbers

\(T_{\text{eff}} = 3000 \text{ K}\)

(Allard et al 1997)
How Good Are the Models?

(Burrows et al. 2001)
How Good Are the Models?

- good qualitative agreement with data
- some missing opacities due to incomplete line lists:
  - H$_2$O in near-IR
  - CaH in optical
  - FeH in near-IR
How Good Are the Models?

NGC6397 globular cluster data (Cool et al. 1996)

$[m/H] = -1.5$ model (Baraffe et al. 1997)

field stars ($[m/H]=0$)
Complications with LTE Modeling

• pressure broadening (Na I, K I; van der Waals), interaction potentials (H$_2$)
  – move atmosphere away from LTE
• micro-turbulent velocity broadening (generally small; 1–2 km s$^{-1}$)
• condensate grain formation and distribution, cloud structure
• chemistry, especially non-equilibrium mixing
• depth of convection zone (10$^{-3} < \tau < 1$)