Giant Planet Interiors

PHY 688, Lecture 17
Mar 6, 2009
Outline

• Review of previous lecture
  – the hydrogen burning limit
  – lithium and deuterium burning
  – atmospheric lithium as an age/mass indicator

• Giant planet interiors
  – comparison to brown dwarfs

• NASA’s Kepler Telescope launches tonight!
  – in search for other habitable worlds
Previously in PHY 688...
The Minimum Main-Sequence Mass

• Derive by equating nuclear energy generation to energy loss through cooling.

\[ \frac{dE}{dt} + P \frac{dV}{dt} = T \frac{dS}{dt} = \dot{\varepsilon} - \frac{\partial L}{\partial M} = 0 \]

• Have expression for \( L(M, \kappa_R, \eta) \)
• Find expression for \( \dot{\varepsilon}(M, \eta) \)
p-p Chain Reaction Rate in Low-Mass Stars Is Decided by the First Step (p+p)

take into account Coulomb coupling
Minimum Main Sequence Mass

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

\[ I(\eta) = \frac{(\eta + \alpha)^{1.509}}{\eta^{1.325}} \]

• \( M_{\text{MMSM}} \) depends on:
  – opacity \( \kappa_R \) (i.e., metallicity \( Z \))
  – He content \( Y \) (through \( \alpha(Y) \))

• \( M_{\text{MMSM}} = 0.075 \, M_\text{Sun} \) at solar \( Y \) (25%), \( Z \) (1.6%)
  – lower for higher \( Y, Z \)
Lithium and Deuterium Burning

Li and H burning: at $> 2.7 \times 10^6$ K

D burning: at $> 4 \times 10^5$ K

(Burrows et al. 2001)
Li and D: Depleted within Few 100Myr

(Burrows et al. 2001)
Lithium is Observable in the Photosphere

(Kirkpatrick et al. 1999)
The Lithium Test for Age/Substellarity

presence of Li:

- youth
- substellar mass

\( \text{and/or} \)

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From Lecture 13: H Phase Diagram

(Burrows & Liebert 1993)
H Phase Diagram: Revisited

- compared to brown dwarfs, the interiors of giant planets are:
  - more strongly degenerate ($\theta \equiv \eta$ in this diagram)
  - more strongly Coulomb-coupled

(Guillot 2006)
Polytropic Index $n$ for Giant Planets

- brown dwarfs are pressure-supported by degenerate non-relativistic electron gas:
  \[ P_e \propto \rho^{5/3}, \text{ i.e.,} \]
  \[ n = 1.5 \]

- stronger electron screening in Coulomb plasma in planetary interiors weakens $P(\rho)$ dependence

(Guillot 2006)
From Lecture 13: Radius vs. Mass

(Burrows & Liebert 1993)
Radius vs. Mass: Comparison with Known Planets

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

- \( n = 1.5 \) 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?

\[ (\text{Guillot } 2006) \]
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

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

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

165–170 K
100 kPa

6300–6800 K
200 GPa

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

Inhomogeneous?

Metallic H ($Y \approx 0.27$)

15000–21000 K
4000 GPa

Ices + Rocks core?

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

(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

(Guillot 2006)
Evolution of brown dwarfs and planets on the H-R diagram

(Burrows et al. 1997)
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The following slides are from Gibor Basri (UC Berkley, Kepler Co-PI)
The Habitable Zone (HZ) in green is the distance from a star where liquid water is expected to exist on the planets surface (Kasting, Whitmire, and Reynolds 1993).
The first 50 known extrasolar planets are also shown along with the planets in our solar system.

The limit for planet detection using Doppler spectroscopy is shown.

The range of habitable planets (0.5 to 10 $M_\oplus$) in the HZ is shown in green.
PHOTOMETRY CAN DETECT EARTH-SIZED PLANETS

- The relative change in brightness ($\Delta L$) is equal to the relative areas ($A_{\text{planet}}/A_{\text{star}}$)

Jupiter: 1% area of the Sun (1/100)

Earth or Venus: 0.01% area of the Sun (1/10,000)

- To measure 0.01% must get above the Earth’s atmosphere

- Method is robust but you must be patient:
  
  Require at least **3 transits, preferably 4** with same brightness change, duration and temporal separation
  
  (the first two establish a possible period, the third confirms it)
Detecting Planets with Transit Photometry
Kepler MISSION CONCEPT

- **Kepler** is the first mission optimized for finding habitable planets (0.5 to 10 $M_{\oplus}$) in the HZ (near 1 AU) of solar-like stars

- Continuously and simultaneously monitor 100,000 main-sequence stars

- Use a one-meter Schmidt telescope: FOV $>100$ deg$^2$ with an array of 42 CCD

- Photometric precision: Noise $< 20$ ppm in 6.5 hours V = 12 solar-like star => 4$\sigma$ detection for one Earth-sized transit

- Mission: Heliocentric orbit for continuous viewing $> 4$ year duration
Kepler Field of View
Potential for Detections

Expected # of planets found, assuming one planet of a given size & semi-major axis per star and random orientation of orbital planes.
Kepler Mission Launch

Mar 6, 2009
10:49pm EST