Giant Planet Structure and Thermal Evolution

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Thanks to: Neil Miller (UCSC), Nadine Nettelmann (Rostock)
Talks Breakdown

Part 1: Big Questions, Input Physics, Solar System Planets

Part 2: Atmospheres and Exoplanets
Transiting Planets, Large and Small

- 100 planets have now been seen to transit their parent stars
  - 94 “hot Jupiters”
  - 4 “hot Neptunes”
  - 2 “super Earths”

- Combination of planet radius and mass yield density - \( \rightarrow \) composition

- Strong bias towards finding mass/large planets on short-period orbits

- July 2007
There is an incredibly diversity of worlds

- We can also characterize these planets, not just find them
• What is the **composition** of giant planets?
• What is the **core mass**?
• How do atmospheric **abundances** relate to interior abundances?
• What is the “**metallicity**” and the **ice/rock** ratio?
• How does **composition** vary from Neptune-like planets (ice giants) to Jupiter-like planets (gas giants)?

• Bulk composition comes from mass and radius—can be observed for solar system planets and exoplanets
• Gravity field yields constraints on density profile—achieved via solar system space missions
• Atmospheric abundances are most reliably achieved by entry probes, can also be determined via spectroscopy, for solar system planets or exoplanets
The Big Questions and How We Try to Answer Them, II

• How do giant planets form?
• Is there one formation mechanism or two?
• If two, what are the observables that discriminate between them?
• How does the disk environment affect final planet properties?

A lot of computer time and ink get used: models and models
• For the solar system planets, gravity field + atmospheric abundances allow for quantitative analysis of the core accretion process

• Radial Velocity (RV) + plus transit observations allow for measurements of planet frequency is a function of mass, which can be compared to population synthesis models
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The Big Questions and How We Try to Answer Them, III

- How does intense **stellar insolation** affect planetary evolution?
- How good is our **input physics**?
- Are we **missing input** physics?
- Can we understand giant planets as a class of **astrophysical objects**?

- We can study mass vs. radius vs. time vs. insolation via transits
- We can probe planetary interiors via dynamic shock experiments and via first-principles calculations
- Beyond the solar system, we can observe planets at Myr ages, Gyrs ages, at 0.01 AU and 100 AU, from Neptune-class to Brown Dwarfs
The Low-Mass Star Giant Planet Connection

**Early 1960s:** Discovery of fully convective Hayashi Phase

**1963:** Theoretical Discovery of Brown Dwarfs by Hayashi & Nakano (1963) and Kumar (1963)

**1966:** Low, observing at 20 μm, finds that Jupiter has an internal energy source (emits more 20 μm flux than it receives from the Sun)

**1968:** Hubbard shows that neither conductive nor radiative transport can bring the observed flux throughout Jupiter’s interior the surface, implying the planet’s interior is warm (10^4 K) fluid, and convective, not cold and solid [Also Zharkov & Trubitsyn in USSR]
Our Planetary Materials

**Hydrogen and Helium**
- Not really gas
- Dense H fluid transitions from molecular to metallic state
- Strongly coupled dense H+ plasma with mostly neutral He

**Planetary Ices**
- Not really ice
- Dense fluid of H$_2$O, CH$_4$, NH$_3$, not necessarily in intact molecules

**Rocks**
- Includes rocks (Mg/Si dominated) and iron
- At boundary between solid and liquid
Hydrogen Phase Diagram

Fortney, Baraffe, & Militzer (2010)

- Plasma (p+e)
- Star 15 M$_{\text{sun}}$
- Sun
- Star 0.3 M$_{\text{sun}}$
- Molecular Fluid (H$_2$)
- Atomic Fluid (H)
- Metallic Fluid (H)
- ICF path
- Jupiter
- Hugoniot
H in fluid plasma phase (liquid metal)

Plasmas is strongly coupled
\[ \Gamma = \frac{e^2}{ak_B T} \]

Plasma is degenerate
\[ \theta = \frac{T}{T_F} \]

Saumon (2009)

\[ \Gamma \approx 20-30, \quad \theta \approx 0.02,\]
Guillot (2005)
Coulomb Repulsion + Degeneracy Leads to Radius nearly independent of Mass

Fortney, Baraffe & Militzer (2009)
Shock Experiments

- Pressure-density
- Temperatures
- Conductivities
Is the ice in Neptune-class planets solid?

- No.
- All evidence for Uranus/Neptune indicates that their interiors are predominantly fluid
  - A fluid “sea” of partially dissociated fluid H$_2$O, NH$_3$, and CH$_4$
  - This is backed up by models of dynamo-generated magnetic field
  - Experiments by Nellis et al. on water and “synthetic Uranus” mixtures
The same as for stars!
The Solar System’s Giant Planets

- Known precisely: Mass, Radius, Age, $T_{\text{eff}}$
- Known well: Gravity Field, Magnetic Field, 1-bar temperature, Albedo
- Data quality scales inversely with distance, especially due to the Galileo Orbiter, Galileo Entry Probe, and Cassini Missions
- No planned Uranus and Neptune Orbiters
Jupiter and Saturn: Current Interior

\[
V_{\text{grav}} = \frac{GM}{r} \left[ 1 - \sum_{n=1}^{\infty} \left( \frac{a}{r} \right)^{2n} J_{2n} P_{2n}(\cos \theta) \right]
\]

\[
J_{2n} = -\frac{1}{Ma^{2n}} \int \int \int \rho(r, \theta) r^{2n} P_{2n}(\cos \theta) dv,
\]

Schematic View of Jupiter and Saturn

Fortney, Baraffe, & Militzer (2010)
Envelope Abundances for Jupiter and Saturn

"Solar" is Lodders (2003)
Evolution of Calculations of Jupiter’s Core Mass

Fortney & Nettelmann (2010)
The Three Temperatures

$T_{\text{eff}}=$ temperature of a blackbody that would emit the same bolometric flux are the planet
This includes intrinsic flux as well as absorbed & re-radiated stellar flux

$T_{\text{int}} = T_{\text{eff}}$ in the absence of stellar flux

$T_{\text{eq}} = T_{\text{eff}}$ in the absence of an interior energy source – set only by absorbed flux

$$T_{\text{eq}}^4 + T_{\text{int}}^4 = T_{\text{eff}}^4$$
Jupiter and Saturn: Thermal Evolution

- Cooling models reproduce Jupiter’s current $T_{\text{eff}}$ reasonably well, given uncertainties in input physics.

- Saturn is far warmer than these same models predict.

- H/He phase separation is thought to be Saturn’s additional energy source.

Hubbard & DeWitt (1985)
Fortney & Hubbard (2003, 2004)

\[
Y_{\text{protosolar}} = 0.275 \pm 0.01 \text{ (helioseismo)}
\]

\[
Y_{\text{Jupiter}} = 0.238 \pm 0.005 \text{ (probe)}
\]

\[
Y_{\text{Saturn}} = 0.18-0.25 \text{ (spectra)}
\]

Including He differentiation is essential to the next generation of Jupiter and Saturn cooling models, but many details (phase diagram, effect of composition gradient are not well understood)
Uranus and Neptune: Current Interior

Fortney, Baraffe & Militzer (2009)
Uranus and Neptune: Current Interior

Fortney, Baraffe & Militzer (2009)
Uncertainties in Understanding the Interiors of Uranus and Neptune

Uranus and Neptune DO NOT have 3 well-defined layers!
Uranus & Neptune: Dramatically revised high-pressure water EOS has an even larger impact than new atmospheres

Simple Hubbard & MacFarlane (1980)-style 3 layer models: H/He, H₂O, rock
For the first time, Neptune models match measured $T_{\text{eff}}$

Gravity fields of both planets also matched (constrains current structure)
Juno at Jupiter, 2016

• Very high order gravity field and magnetic field observations
• Microwave spectroscopy of deep atmosphere to determine water and ammonia abundances

Cassini at Saturn, until 2017

• Extended-extended mission (XXM) will map gravity field before plunging into the atmosphere
Takeaway Message for the 4 Planets

Jupiter:
- Cooling models modestly overestimate $T_{\text{eff}}$ at 4.5 Gyr
- Probably the current H EOS overestimates interior temperatures, which was already suggested by lab data
- Core mass still not well constrained

Saturn:
- Cooling models greatly underestimate $T_{\text{eff}}$ at 4.5 Gyr
- He rain clearly still needed
- Core mass well constrained at 10-20 $M_E$

Uranus:
- Cooling models greatly overestimate $T_{\text{eff}}$ at 4.5 Gyr
- Tiny interior flux still not well understood
- Cooling models match $T_{\text{eff}}$ at 4.5 Gyr

Neptune:
- One model can match gravity field and $T_{\text{eff}}$, for the first time
- Even more significant dichotomy with Uranus
- If entire H/He and water-rich envelopes are freely convecting, what impact on magnetic field generation?

Stanley & Bloxham (2006)
Model Atmospheres

There are quite a few ways of doing this

- P-T Profile
  - Dayside
  - Nightside
  - Terminator
  - Rad. Equil.?

- Chemistry
  - Equilibrium
  - Noneq—Mixing
  - Photochemistry
  - Clouds?

- Opacities
  - Optical
  - IR
  - UV?
  - Complete?

Observables: Emitted & Scattered Light
• Radiative-convective atmosphere model yields $S$ at atmosphere bottom, or $T$ & $P$ at tau=100
• Structure model gives a snapshot of log $g$ and $S$, the atmosphere grid is interpolated to yield $T_{\text{eff}}$
Atmospheres: Structure, Chemistry, Effect on Evolution

Elemental Abundances

What is a “hot Jupiter”? 

Diversity!

Made by Fortney
Pressure-Temperature ($P$-$T$) profiles from Jupiter to a 3000K M dwarf star

adapted from Hubbard et al. (2002)
Hot Jupiters: Fully Radiative Atmospheres

- Shallower atmospheric T-gradient leads to slower interior cooling, and larger radius at a given age

- Temperature structure evaluated analytically in the gray approximation by B. Hanson (2008) and T. Guillot (2011)

Fortney et al. (2007)
Methods for Characterizing the Atmospheres of Transiting Planets

**Secondary Eclipse**
See thermal radiation and reflected light from planet disappear and reappear
- Amplitude: ~0.1%
- Time Scale: 1-5 hours

**Transit**
See radiation from star transmitted through the planet’s atmosphere
- Transit depth: ~1%
- Absorption feature: ~0.01%
- Time Scale: 1-5 hours

**Orbital Phase Variations**
See cyclical variations in brightness of planet
- Amplitude: ~0.01-0.1%
- Time Scale: 30-100 hours
Spitzer Observations: The View from Above

Charbonneau et al. (2008)
Barman (2007)
Swain et al. (2008)
Tinetti et al. (2008)
Snellen et al. (2010)

Atomic Lines

$\text{Na}$
$\text{K}$
$\text{H}_2\text{O}$

$\text{H}_2\text{O}$
$\text{CH}_4$

Tinetti et al. (2008)
Swain et al. (2008)
Spectroscopy of thermal infrared light emitted by the planets

- Jupiter, 1969
- HD 189733b, 2008

For most transiting planets, spectra are difficult to obtain, so we can only measure the brightness in a few wide wavelength bands.
Study the group as a class of planets:
For instance, Tidal and Thermal Evolution of hot Jupiters

- 100 planets have now been seen to transit their parent stars
  - 94 “hot Jupiters”
  - 4 “hot Neptunes”
  - 2 “super Earths”

- Combination of planet radius and mass yield density -> composition

- Strong bias towards finding mass/large planets on short-period orbits
There is an incredibly diversity of worlds

- We can also **characterize** these planets, not just find them
There is considerable diversity amongst the known transiting planets. Radii for planets of similar masses differ by a factor of two, which cannot happen for pure H/He objects.
Building a Model, I: Standard Cooling and Contraction

1 M_J planet with a 10 M_E core, at 0.05 AU from the Sun

Miller, Fortney, & Jackson (2009)
At Gyr ages, \( \sim 1.3 \, R_J \) is the largest radius of a standard cooling model.

Fortney et al. (2007)
Building a Model, II: Additional Interior Power

Miller, Fortney, & Jackson (2009)

1 $M_J$ planet with a 10 $M_E$ core, at 0.05 AU from the Sun
Planet Radius vs. Irradiation Level

A trend is now clear: The largest radius planets are the hottest.
Explaining Large Radii

An area of active research!

Evolution of “51 Pegasus b-like” planets

T. Guillot¹ and A. P. Showman²

ON THE TIDAL INFLATION OF SHORT-PERIOD EXTRASOLAR PLANETS¹

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OBLIQUITY TIDES ON HOT JUPITERS

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The effect of evaporation on the evolution of close-in giant planets

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POSSIBLE SOLUTIONS TO THE RADIUS ANOMALIES OF TRANSITING GIANT PLANETS

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HEAT TRANSPORT IN GIANT (EXO)PLANETS: A NEW PERSPECTIVE

Gilles Chabrier and Isabelle Baraffe¹,²

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TWO CLASSES OF HOT JUPITERS

Brad M. S. Hansen¹ and Travis Barman²

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TIDAL HEATING OF EXTRASOLAR PLANETS

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INFLATING HOT JUPITERS WITH OHMIC DISSIPATION

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THE MECHANICAL GREENHOUSE: BURIAL OF HEAT BY TURBULENCE IN HOT JUPITER ATMOSPHERES

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INFLATING AND DEFATING HOT JUPITERS: COUPLED TIDAL AND THERMAL EVOLUTION OF Known TRANSITING PLANETS

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COUPLED EVOLUTION WITH TIDES OF THE RADIUS AND ORBIT OF TRANSITING GIANT PLANETS: GENERAL RESULTS

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THERMAL TIDES IN FLUID EXTRASOLAR PLANETS

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CASSINI STATES WITH DISSIPATION: WHY OBLIQUITY TIDES CANNOT INFLATE HOT JUPITERS

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Example XO-4b: Inflated, Current $e \approx 0$, but not well constrained

Explaining Large Radii: Two Recent Contenders

**Thermal Tide**
- Arras & Socrates (2010)

**Ohmic Dissipation**
- Batygin & Stevenson (2010)
Building a Model, II: Additional Interior Power

- Lower mass planets more easily influenced by a given magnitude of power source
- Power levels are generally small compared to Irradiation from the parent star $\sim 10^{29}$ erg/s
- Transit radius effect only important at low gravity

Miller, Fortney, & Jackson (2009)
Degeneracy: Many compositions yield the same mass/radius

Nettelmann et al. (2010)
But as we know from Uranus and Neptune, it is actually worse than this
Transits in multi-planet systems: A path towards direct interior constraints: Tidal Love #, $k_{2b}$

The calculation of $k_{2b}$ is straightforward (Sterne 1939),

$$k_{2b} = \frac{3 - \eta_2(R_p)}{2 + \eta_2(R_p)} ,$$  \hspace{1cm} (13)

where $\eta_2(R_p)$ is obtained by integrating an ordinary differential equation for $\eta_2(r)$ radially outward from $\eta_2(0) = 0$,

$$r \frac{d\eta_2}{dr} + \eta_2^2 - \eta_2 - 6 + \frac{6\rho}{\rho_m}(\eta_2 + 1) = 0 ,$$  \hspace{1cm} (14)

Wu & Goldreich (2005)
Batygin et al. (2009)
Ongoing Mass Loss

Vidal-Madjar et al. (2003): “evaporative” mass loss

• Observed for ~3 planet but likely common to all hot Jupiters
• Probably has little effect on evolution of Jupiter-class planets, but likely important for smaller Neptune-class planets
CoRoT-7b

Valencia et al. (2010)
Direct Imaging: Probes of Early Planet Evolution

Marois et al. (2010)
Suites of Thermal Evolution Models for Planets and Brown Dwarfs

The standard references are:
Burrows et al. (1997)
Chabrier et al. (2000)
Baraffe et al. (2003)
Saumon & Marley (2008)

What assumption goes into the initial condition for these models, and are they correct?

Investigated in Marley, Fortney, et al. (2007)
“Although all these calculations may reliably represent the degenerate cooling phase, they cannot be expected to provide accurate information on the first $10^5$-$10^8$ years of evolution because of the artificiality of an initially adiabatic, homologously contracting state.

--Stevenson (1982)
Hubickyj, Bodenheimer, & Lissauer implementation of the core-accretion model

1. Planetesimals $\rightarrow$ core
2. Gas accretion rate grows and surpasses solid accretion rate
3. Runaway gas accretion
4. Limiting gas accretion $\rightarrow$ how fast can nebular gas be supplied? Gas arrives at a shock interface.
5. Accretion terminates $\rightarrow$ isolation stage (cooling & contraction)

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Stahler et al. (1980a)
Post-Formation Entropy

- Internal specific entropy 1 Myr after formation
- Entropy monotonically decreases with age
- Low post-formation entropy $\rightarrow$ small radii & low luminosity
- Quite dependent on the treatment of the accretion shock!
- At higher masses, a higher % of mass has passed through shock

Marley, Fortney, et al. (2007)
1. Core-accretion planets are formed with significantly smaller entropy and radii

2. $t_{KH} \propto 1/LR \propto e^{-2.8S}$, meaning evolution is initially much slower for the core-accretion planets

3. Initial conditions are not forgotten in “a few million years,” but rather, 10 million to 1 billion.

4. Initial $T_{\text{eff}}$ values cluster around 600-800 K

Marlet et al. (2001)
If these planets did form by core accretion, then perhaps the “hot start” is closer to reality.

Starting in late 2011, the Gemini Planet Imager (GPI) on Gemini South and SPHERE on the VLT, specially designed “extreme AO” instruments, should image 100-400 additional giant planets.

The field is going from 4 objects to hundreds, and then thousands.
A measurement of mass-radius yields important information about the structure of a gas giants.
Mass-radius tells us less about the structure of Neptune-class planets, broadly defined.
Work is progressing on understanding the visible atmosphere.
No clear winner yet regarding what is inflating the planets, but emerging trends will help to clarify this issue.
Reference 1


Saumon, D., 2009: To see the inside of a planet in a drop of deuterium, Astrophysics and Space Science, Vol. 322, 123-127.


Reference 2


