The interior structure of planets

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I. Latest news regarding giant planet structures

II. Structure of Earth-like and super-Earth planets

III. Mass-radius and mass-metallicity relationships of giant planets
I. Giant planet structures

The standard picture for our solar system giant planets:

- Internal structure models commonly based on the “two or three-layer” picture
  \( (\text{Militzer et al. 2008; Fortney & Nettelmann 2010; Helled & Guillot 2013, etc…}) \)

\begin{itemize}
  \item Layer 1: outer envelope with \( \text{H}_2 \), depleted \( \text{He} \) and \( Z_1 \)
  \item Layer 2: inner envelope with metallic \( \text{H} + \text{He} + Z_2 \)
  \item Layer 3: central core (rock/water)
\end{itemize}

(2-layer: core of rock/\( \text{H}_2\text{O} \) and isentropic mantle of \( \text{H}/\text{He} \))

Different composition between layer 1 and layer 2:
- First order transition metallic \( \text{H} \) - molecular \( \text{H}_2 \) (\( P \sim 1-2 \text{ Mbar} \)) \( \text{Saumon & Chabrier 1992} \)
- Phase separation between \( \text{H} \) and \( \text{He} \) (\( \text{He} \) droplets rain out) \( \text{Smolugovsky 1973; Salpeter 1973} \)

- Layers **fully convective** (i.e adiabatic)
Comprehensive equation of states for H and He based on ab initio calculations (Becker et al. 2014; Militzer et al. 2013; Chabrier et al. 2018)

- **Pressure-induced immiscibility of H and He** (*Salpeter 1973*) —>
  - He rain out occurs at ~ 1-3 Mbar (*Militzer et al. 2016*)
    (deeper, at higher T, He becomes miscible again)
  - Rain out of He from exterior to interior which explains low He abundance (Y ~ 0.23) measured at surface of Jupiter by Galileo entry probe

- **Core erosion** (*Stevenson 1985*)
  - Core heavy material can become soluble in liquid metallic hydrogen
  - Ab initio Gibbs free energy calculations (*Soubiran et al. 2017*) show that all possible main species in a core (H2O, SiO2, MgO, Fe) are miscible in the metallic hydrogen
  - Core can be progressively eroded by the surrounding H-He envelope
• Exact nature of core under jovian conditions is uncertain

→ **liquid or solid** depending on its composition

- water would be a dense plasma *(French et al. 2009)*

- rocky material MgO would be solid *(Wilson & Militzer 2012)*

- rocky material SiO₂ is currently **solid** under jovian core conditions but could have been **liquid** at younger ages (when the planet had a hotter core) *(Gonzales-Cataldo 2014)*
Departure from adiabatic structure in planetary interiors:
(Stevenson & Salpeter 1977; Stevenson 1979; Chabrier & Baraffe 2007; Leconte & Chabrier 2012, 2013; Kurokawa & Inutsuka 2015; Vazan et al. 2015; Nettelmann et al. 201)

- Presence of a molecular weight gradient $\nabla_\mu$
  
  $\nabla_{\text{ad}} > \nabla_T + \nabla_\mu \chi_\mu / \chi_T$  \textit{(Ledoux criterion)}

$\Rightarrow$ «layered convection»: system of convective layers + thiny diffusive layers
 \textit{(double diffusive convection or semiconvection)}

Process which may occur in a medium where two substances diffuse at a different rate

\textbf{3D numerical simulations:}

$\Rightarrow$ Layers can form in low-Pr (< 1) double diffusive convection
(Rosenblum et al. 2011; Mirouh et al. 2012; Wood et al. 2013)
Presence of double-diffusive convection in Jupiter and Saturn compatible with previous observational constraints (Leconte & Chabrier 2012, 2013)

Reproduce the gravitational moments $J_2$ and $J_4$ (Pioneer, Voyager)

- Jupiter: $M_{\text{core}} = 0 - 0.5 \, M_\oplus$ \vspace{2pt}
  $M_Z = 41-63 \, M_\oplus$
  \vspace{2pt}
  $Z_{\text{tot}} = 13\% - 20\%$ (previous: $Z_{\text{tot}} = 2.5\% - 12\%$ \vspace{2pt}
  $M_Z < 40 \, M_\oplus$)

Inhomogeneous models for Jupiter and Saturn would be significantly more enriched in heavy material (30\%-60\% more) than adiabatic models.

Now confirmed by new Jupiter models using Juno’s constraints (see Debras’s talk)
Impact on the erosion of cores: toward a more complex interior structure of jovian planets

*(Moll, Garaud, Mankovitvh, Fortney 2017)*

Time scale of this erosion process remains uncertain:

- ~ a few Myr for single solid/fluid interface *(Soubiran et al. 2017)*
- slower erosion rate for staircases interface
Structure of Jupiter (and giant planets in general) much more complicated thanks to recent constraints from Juno:

most likely eroded core with layered convection in the interior (see Florian Debras’s talk!)

→ upward mixing of heavy elements

(Wahl et al. 2017; Debras & Chabrier 2018)

Previous standard 2-3 homogeneous, adiabatic layer models are much too simplistic!
Similar efforts devoted to EOS are underway for water and rocky material that spans regime from Earth-like planets to core of giant planets.

(French et al. 2009; Soubiran & Militzer 2014; Hakim et al. 2018; Mazevet et al. 2018)

II. Earth-like and super-Earth planets

Observed mass and radius of super-Earths are used to infer their internal structure as well as surface and internal dynamics of exoplanets (e.g., Valencia et al., 2006; Seager et al., 2007; Wagner et al., 2011).

—> EOS used in most studies are usually extrapolated in the regime of super-Earth or calculated at zero temperature.
Water dominated planets

Recent progress on ab initio EOS for water

T = 300K

Seager et al. 2007 (T=0K)

T = 1000K

(Mazevet et al. 2018)
Comparison of current EOS for water with high pressure experiments

Previous widely EOS from ANEOS and SESAM (Baraffe et al, 2008) should be ruled out for planetary modelling though still in use (Miguel et al. 2016; Thorngren et al. 2017, etc…)

(Mazevet et al. 2018)
Temperature dependence of the mass-radius relationship

The effect of T is significant and cannot be neglected when assessing the interior structure of super-Earths (as already pointed out by Baraffe et al. 2008 and Thomas & Madhusudan 2016).
Rocky Super Earths

Recent progress on the EOS of Fe

Iron is usually assumed to be the major element in the core of super-Earths

but most current EOS are extrapolated: Vinet formulation in Valencia et al. (2007) and Seager et al. (2007) or BM3 formulation in Dorn et al. (2015):

EOS fitted to data of Fe at P=200-300 GPa but extrapolated to 5-20 TPa!!

(Central $P$ for a $10 \, M_{\text{Earth}}$ is $4 \, \text{TPa}$)

Hakim et al. 2018: derivation of EOS based on ab initio methods for Fe up to 137 TPa

$\rightarrow$ up to 20% difference in density between previous EOS at 10 TPa
M-R relationships assuming different core radius fraction and mantle composition

Earth-like $r_c \rightarrow 50$

Mercury-like $r_c \rightarrow 80$

(Hakim et al. 2018)
Main conclusions based on this improved Fe EOS:

1) Improved EOS can reduce some of the degeneracy in interpretation of mass-radius
2) Uncertainties in composition ➔ spread of mass-radius curves that can overlap

⇒ significant limitation to accurately infer the interior structure of rocky super-Earths

Expected accuracy of 3% in R and 10% in M with upcoming missions (TESS, CHEOPS, JWST, PLATO) *(Hatzes et al. 2016)*

⇒ Modelling uncertainties will dominate over observational uncertainties

Knowledge of stellar composition (Fe/Si, Mg/Si) may help mitigating the M-R degeneracy *(Dorn et al. 2015; Santos et al. 2017)*
III. Some thoughts on Mass - radius and mass-metallicity relationships for giant planets

• **Core erosion**
  
  —> upward transport of heavy material from the deep interior

  ➡️ May affect atmospheric abundances

  ➡️ \( Z_{\text{atmosphere}} \) signature of complex physical/chemical processes happening deeper inside rather than signatures of formation process

• **Non adiabatic interior structure (layered convection)**

  ➡️ Complication if presence of layered convection (*as in Jupiter, see Debras’s talk*): two planets of same M and same R can have different heavy material content (\( M_Z \)) if one is fully convective and the other one has layered convection
• The problem of inflated hot transiting giant planets

- inflation of irradiated giant planets renders the determination of heavy element content (and thus of a mass - $M_\text{z}$ relationship) even more difficult and uncertain

Understanding the mechanism(s) may help

$\rightarrow$ observations point toward an incident stellar flux driven mechanism \textit{(Laughlin et al. 2011)}
- **Ohmic dissipation:** *(Batygin & Stevenson 2010; Perna et al. 2010)*  
  —> Electromagnetic interactions between atmospheric winds and planetary magnetic fields  
  —> currents penetrating in the interior  
  *Ohmic heating in the interior* $\dot{E} = J^2/(\rho \sigma)$

*Thorngren & Fortney (2018):* Recent claim of evidence for the ohmic dissipation model based on bayesian analysis

**Some word of cautions:**  
(i) Use M-M$_z$ relation for non irradiated planets and apply it to irradiated ones  
(ii) Finds heating efficiency that declines at high flux (gaussian shape) —> could be compatible with models of ohmic dissipation *(Batygin et al. 2011; Menou 2012; Ginzburg & Sari 2016)*

*Interesting study but still many uncertainties and assumptions in the analysis to claim that ohmic dissipation is THE mechanism….*
Advection of potential temperature:

- **Tremblin et al. (2017)**
  - Irradiation process $\Rightarrow$ longitudinal mass flow
  - In a **steady state**, mass conservation implies that resulting longitudinal mass flow is balanced by a combination of meridional and vertical mass flows.

Vertical mass flux $\Rightarrow$ advection of potential temperature $\Rightarrow$ **adiabatic profile**

- At depth, the atmosphere reaches hotter adiabatic structure.
- Larger radius for a given mass.

**Note:** this process may also become less efficient at high fluxes because of increasing dissipation effects due to faster winds (e.g. shocks).

The interesting case of re-inflated planets:

- Planets with radius increasing over time as the parent star evolves off the Main Sequence (**Lopez & Fortney 2016; Grunblatt et al. 2017**)

- Interesting because used to rule out delayed cooling models.

**Note:** Is it necessarily the same mechanism as the one affecting main sequence host star planets??
Huge progress on calculations of equation of states for planetary material at high pressure and constraints from Juno on Jupiter:

⇒ Internal structures of planets are extremely complicated

⇒ Current structure models for exoplanets (heavy core + fully convective H/He/Z envelope) implying that atmospheric abundances reflect mixing ratios of heavy elements within the H/He envelope are much too simplistic.

➤ This should be kept in mind when deriving from these simplistic models mass-metallicity relationships or $Z_{\text{atmosphere}} - Z_{\text{bulk}}$ relationships.