Giant planets:  
far out, close-in, and deep inside  

N. Nettelmann, B. Holst, A. Becker, M. French,  
R. Redmer (U Rostock)  
T.R. Mattsson (SNL)
Outline

• H-EOS and Jupiter in 1995-‘99
• H-EOS and Jupiter in 2008-‘09
• H-EOS and Jupiter in 2010-‘11
  → primary objectives for CY11, CY12
• H/He demixing and Saturn
• ices in Uranus & Neptune
• ice in close-in big planets?
  → future project objectives for CY12+
H EOS in 1995-'99

Experimental and theoretical principal Hugoniots predict a high maximum compressibility ~ 5.5.

- Gas-Gun (LLNL): Holmes et al. 1995, PRB
- LM Ross: Ross 1998, PRB
The SCvH-ppt EOS predicts a PPT in Jupiter at 1.7 Mbar and 6800 K.
Jupiter in 1995-‘99

Jupiter according to SCvH-ppt EOS

- layer boundary where metallization begins (1.7 Mbar)
- core mass 5-10 Mₚ
- SCvH-i: core mass 0-5 Mₚ

Models:
- Guillot (1999a,b), Science, P&SS
- Guillot et al. (1994a,b) Icarus
- Chabrier et al. (1992), ApJ
- Nettelmann et al. (2008), ApJ

EOS:

1.7 Mbar 6800 K
40 Mbar 20000 K

\[ \text{H}_2 \]
\[ \text{He} \]
\[ \text{He}^{2+} \]
\[ \text{PPT} \]
\[ \text{metallic envelope} \]
\[ \text{molecular envelope} \]
\[ \text{core} \]
The overall shape of the Z-pinch data and the modified Omega laser data is best reproduced by FT-DFT-MD simulation data.

- Z-machine (SNL): Knudson et al. 2004, PRB
- Omega laser (Rochester): Hicks et al. 2009, PRB
- modified Omega data: Knudson & Desjarlais 2009, PRL
- FVT: Juranek & Redmer 2000, JCP
- PIMC: Militzer & Ceperley 2000, PRL
- FT-DFT-MD: Holst et al. 2008, PRB
Jupiter in 2008-‘09

Jupiter according to LM-REOS-2008

- layer boundary
- free parameter
- continuous metallization
- $Z_1 << Z_2$

EOS:
- Holst et al. 2008, PRB + FVT
- French et al. 2009, PRB + Sesame 7150
- Kietzmann et al. 2007, PRL + Sesame 5761

models:
- Fortney & Nettelmann 2009, SSR
zero-mass core implies maximum envelope metallicity

\[ Z_1 \text{ [solar Z]} \]

\[ Z_2 \]

\[ M_{\text{core}} \text{ [M_{Earth}]} \]

\[ P_{1-2} \text{ [Mbar]} \]
The maximum envelope metallicity lies below the observational limit.

Galileo entry probe data:

- C
- N
- S
- Ar
- Kr
- Xe

Pressure $P_{1-2}$ [Mbar]:

- $Z_1$
- $Z_2$
- $M_{core}$

Metallicity $Z$ [solar $Z$]:

- $N_X$ [solar $N_X$]
the minimum metallicity implies a maximum core mass

Galileo entry probe data

Jupiter in 2010-’11 (H-REOS-2010)
Jupiter according to LM-REOS-2010

- 1 bar
- 170 K
- 8 Mbar
- 11050 K
- 42 Mbar
- 19000 K

- He
- H
- H²
- H⁺

- Metallization
- Layer boundary for metals and helium
- Small core

understanding the relation between H EOS and Jupiter adiabat... (wip)

The differences between H-REOS-2010 and H-REOS-2008 in $\rho(p,T)$ and $u(T,P)$ seem equally important for the Jupiter adiabat.

The plot shows the relative difference in density, internal energy, and Jupiter adiabat with respect to pressure (in Mbar). The simulations use different numbers of particles per box:
- H-REOS 2008: $N=64$
- H-REOS 2010: $N=512$
Proposal 01/2011, primary objective:
Measure the H EOS at ~1 Mbar and ~5000 K (~0.55 g/cc) to high accuracy.
ab initio H EOS 2010

SCvH-ppt:
1\textsuperscript{st} order phase transition with $T_{\text{crit}} = 15000 \text{ K}$

H-REOS 2010:
1\textsuperscript{st} order phase transition with $T_{\text{crit}} = 1500 \text{ K}$

- both EOS: plasma phase transition at $P = 1 - 3 \text{ Mbar}$, $\rho = 0.5 - 1 \text{ g/cm}^3$
- H-REOS: PPT at $T < T_{\text{crit}} = 1500 \text{ K}$ cannot be a reason for the layer boundary

(Lorenzen, Holst, Redmer 2010)
The steep rise in electric conductivity indicates a non-metal-to-metal transition.

H-REOS 2010: 1st order phase transition with $T_{\text{crit}}=1500$ K

Proposal 01/2011, primary objective:
Test the prediction of a first order liquid-liquid phase transition.
Saturn

- mass: $95 \text{ M}_{\text{Earth}}$, radius: $9 \text{ R}_{\text{Earth}}$
- orbital distance: 9.5 AU
Energy balance: \[ L - L_\odot = \frac{dE_{\text{int}}}{dt} \]

with \[ L = 4\pi R_p^2 \sigma T_{\text{eff}}^4 \]

Saturn is unusually luminous.

- Saumon et al. (1992), ApJ
- Fortney & Hubbard (2003), Icarus
Saturn, cooling curve

Energy balance:

\[
4\pi R_p^2 \sigma \left( T_{\text{eff}}^4 - T_{\text{eq}}^4 \right) = \frac{dE_{\text{int}}}{dt}
\]

Saturn is unusually luminous.

Solution:

Helium sedimentation leads to additional energy release

Saturn is unusually luminous.

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Saturn is unusually luminous.
Energy balance:

\[ 4\pi R_p^2 \sigma (T_{ef f}^4 - T_{eq}^4) = \frac{dE_{int}}{dt} \]

Simulations of H/He mixtures predict demixing in Saturn

- Lorenzen et al. (2009), PRL
- Morales et al. (2009), PNAS

Solution:
Helium sedimentation leads to additional energy release

- demixing
- 3 Mbar 6600 K
Energy balance:

\[ 4\pi R_p^2 \sigma (T_{\text{eff}}^4 - T_{\text{eq}}^4) = \frac{dE_{\text{int}}}{dt} \]

Simulations of H/He mixtures predict demixing in Saturn

Solution:
Helium sedimentation leads to additional energy release

Future proposal objective:
Confirm demixing of hydrogen and helium at conditions relevant to Jovian planets
Voyager II flyby 1986

Uranus

- Mass: $14.5 \, M_{\text{Earth}}$, Radius: $4 \, R_{\text{Earth}}$
- Orbital distance: 19.2 AU
Uranus' luminosity is unusually low.

Explanations?
- energy flux
- diffusion \( \ll \) convection

Uranus' low luminosity is an important riddle of planetary science.
Uranus, composition

The ice mass fraction can be up to 85% (Neptune similar).
water in Uranus

Uranus interior model assuming all ices are $\text{H}_2\text{O}$

- The ice mass fraction can be up to 85% (Neptune similar).

- The ionic shell is consistent with magnetic field models.

- A superionic layer alone does not explain a stable interior.

- Redmer, Mattsson, Nettelmann, French (2011), Icarus
ices in Uranus

Uranus interior model with diamond sedimentation

- Conducting
- \( \text{H}_2\text{O}, \text{NH}_3 \)
- \( \text{He} \)
- \( \text{H} \)
- 5 Mbar 6000 K
- 0.1 Mbar 2100 K
- P, T 76 K

CH\(_4\) phase separation into \( \text{H}_2 \) (rising) and diamond (sinking) may cause
- a diamond layer
- an inhomogeneous, stable layer

Future proposal objective:

Measure carbon clustering in water-methane mixtures at 6000 K and 1 Mbar.

Knudson & Desjarlais (2008) (exp. & sims. on carbon)
Hirai et al. (2009), PEP (diamond anvil exp. on methane)
Chau et al. (2011), Nat. comm. (sims. on synthetic Uranus mixtures)
Water in close-in exoplanets

Water-ice most likely does not occur in the interior of any known big planet.

Hot Neptune GJ436b:
- $M_p = 23.2 \, M_E$
- $R_p = 4.2 \, R_E$
- $a = 0.03 \, \text{AU}$

Super-Earth GJ1214b:
- $M_p = 6.5 \, M_E$
- $R_p = 2.7 \, R_E$
- $a = 0.017 \, \text{AU}$

Water ice most likely does not occur in the interior of any known big planet.

Future proposal objective:

Confirm the superionic phase of water at ~2 Mbar and ~4000 K.
Summary

Uncertainties in the Jupiter adiabat around 1 Mbar are mapped onto different Jupiter interior models.

proposal: perform multiple shock compression on pre-cooled D$_2$ at Z

Ab initio H EOS predict a PPT at low temperatures off the Jupiter adiabat

proposal: perform shock-ramp compression (on N$_2$) and measure T, $\sigma$

Saturn‘s high luminosity may be explained by He rain

proposal: confirm experimentally H/He phase separation

Uranus low‘ luminosity may be explained by diamond rain

proposal: develop diagnostics for detecting diamond in water

Water in close-in exoplanets is not in an ice phase.

proposal: confirm experimentally the existence of superionic water