NON-CONGRUENT PHASE TRANSITIONS IN INTERIORS OF GIANT PLANETS

Igor Iosilevskiy

Moscow Institute of Physics and Technology (State University)
1967

*Nature* 215 (1967);
Internal Structure and Energy Emission of Jupiter
R. Smoluchowski
Princeton University Princeton, New Jersey

Jupiter emits much more energy than it absorbs. Explanations of the source of this heat depend upon our knowledge of its interior and of the behavior of condensed matter at very high temperatures and pressures.

1968 -1970

Norman & Starostin, *Plasma Phase Transition Concept*

1972

Kormer et al. (Russian Nuclear Center (Sarov)),
*Density jump in quasi-isentropic compression of hydrogen (P~ 3 Mbar)\* - Plasma Phase Transition - ?
1977

**Voyager** spacecrafts mission to Saturn

- Launch (1977)
- Start of Jupiter exploring (1979)
- Start of Saturn exploring (1980)
- Voyager mission is still valid (2007)

**Phase Separation in Giant Planets:**
Jonathan J. FORTNEY, William B. HUBBARD
Icarus, 164 (1) 2003

Atmospheric elemental abundances in Jupiter and Saturn
(*mass fractions*)

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1977

Stevenson & Salpeter, Astrophysical Journal, Suppl. 35 (1977)
- The phase diagram and transport properties for hydrogen-helium fluid planets (p.221-237)
- The dynamics and helium distribution in hydrogen-helium fluid planets (p.239-261)

1977

Galileo spacecraft mission to Jupiter

- Launch (1989)
- Start of Jupiter exploring (1995)
- The end of Galileo mission (Sept. 21, 2003)

Phase Separation in Giant Planets:
Jonathan J. FORTNEY, William B. HUBBARD
Icarus, 164 (1) 2003

Atmospheric elemental abundances in Jupiter and Saturn
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### 2. Dense Multi-Ionic Materials
- Microscopic Correlations and Phase Diagrams for Dense Multi-Ionic Plasmas
- C. Ogata, H. Iyetomi, S. Ichimura, and H. M. Van Horn
- Crystallography of Dense Binary Ionic Mixtures
- Application to White Dwarf Cooling Theory
- C. Chabrier and L. Segretain
- Electronic Structure and Enthalpy of Hydrogen and Helium Mixtures
- M. Ross, J. E. Klee, K. J. Schafer, and T. W. Barbee III
- Plasma Phase Transition in Hydrogen-Helium Plasmas
- M. Schlages, M. Bonitz, and T. Tschitschkan

### 4. Astrophysics I: Giant Planets, Brown Dwarfs, and the Sun
- Giant Planets and the Plasma Phase Transition of Hydrogen
  - D. Saumon, G. Chabrier, W. B. Hubbard, and J. I. Lunine
- Seismology of Jovian Planets and Brown Dwarfs
  - M. S. Marley
- Strongly Coupled Plasmas in Uranus and Neptune
  - W. B. Hubbard
- Recent Theoretical Results on Brown Dwarf Properties and Evolution
  - J. I. Lunine, D. Saumon, W. B. Hubbard, and A. S. Burrows

#### The Heavy Element Contribution to the Equation of State of the Solar Interior: The Diagnostic Potential of Helioseismology
  - W. Däppen
- Isochores of a Quantum Plasma Near the Fully Ionized Limit
  - Application to the Sun
  - A. Perez, G. Chabrier, and A. Alastuey

### 5. Astrophysics II: Degenerate Stars
- Kinetic Properties of Neutron Star Cores
  - D. G. Yakovlev
- Reduction of Direct Urca Process by Nucleon Superfluidity in Neutron Star Cores
  - K. P. Levenfish and D. G. Yakovlev
- Topics on the Equation of State in Metals and Cold Stars
  - D. Lai and S. L. Shapiro

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**Chabrier, Saumon, Hubbard & Lunine**


**The molecular-metallic transition of hydrogen and the structure of Jupiter and Saturn**

**Saumon, Hubbard, Chabrier & Van Horn**


**The role of the molecular-metallic transition of hydrogen in the evolution of Jupiter, Saturn, and brown dwarfs**
Expected presence of «plasma phase transition» in interiors of Jupiter and Saturn


Fig. 3.—Adiabats computed from the EOS described in § 2 with a helium mass fraction $Y = 0.24$. The heavy solid line is the coexistence curve of the plasma phase transition and the critical point is indicated by a dot. Solid lines are computed from the EOS with PPT, dashed lines from the interpolated hydrogen EOS (see text). The temperature of the adiabats at the 1 bar pressure level is, from left to right: 135 (Saturn), 165 (Jupiter), 1500, and 3500 K. In a
4. ASTROPHYSICS I: GIANT PLANETS, BROWN DWARFS, AND THE SUN
   GIANT PLANETS AND THE PLASMA PHASE TRANSITION OF HYDROGEN
   D. Saumon, G. Chabrier, W. B. Hubbard, and J. I. Lunine 111
   SEISMOLOGY OF JOVIAN PLANETS AND BROWN DWARFS
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   W. B. Hubbard 131
   RECENT THEORETICAL RESULTS ON BROWN DWARF PROPERTIES AND EVOLUTION
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   THE HEAVY-ELEMENT CONTRIBUTION TO THE EQUATION OF STATE OF THE
   SOLAR INTERIOR: THE DIAGNOSTIC POTENTIAL OF HELIOSEISMOLOGY
   W. Däppen 147
   ISOCHORES OF A QUANTUM PLASMA NEAR THE FULLY IONIZED LIMIT.
   APPLICATION TO THE SUN
   A. Perez, G. Chabrier, and A. Alastuey 151

5. ASTROPHYSICS II: DEGENERATE STARS
   KINETIC PROPERTIES OF NEUTRON STAR CORES
   D. G. Yakovlev 157
   REDUCTION OF DIRECT URCA PROCESS BY NUCLEON SUPERFLUIDITY
   IN NEUTRON STAR CORES
   K. P. Levenfish and D. G. Yakovlev 167
   TOPICS ON THE EQUATION OF STATE IN METALS AND COLD STARS
   D. Lai and S. L. Shapiro 171
1992
Launch of INTAS-93-66 Project, *Equation of State of Uranium Dioxide up to the Critical Point*

1997
Finish of the first stage of INTAS Project

*Conference on EOS of matter under extreme conditions, Elbrus*

1997 - 2007

**Cassini-Huygens mission to Saturn**

- **Launch** *(Oct. 1997)*
  - Perturbation maneuvers
    - Venus-2 *(April 1998, June 1999)*
    - Earth *(August 1999)*
    - Jupiter *(December 2000)*
  - **Start of Saturn Exploring** *(June, 2004)*
Start of Saturn exploring by Cassini-Huygens

Iosilevskiy I., *Non-congruent phase transitions in astrophysical objects*

International Workshop
*Equation-of-State and Phase-Transitions in Ordinary Astrophysical Matter*
Leiden, Lorentz Center
(June, 2004)
Dominating hypothesis:
Jupiter & Saturn were formed simultaneously (~4.5 GYr) from the protoplanetary plasma with composition similar to protosolar.

Phase Separation in Giant Planets:
Inhomogeneous Evolution of Saturn

Jonathan J. FORTNEY, William B. HUBBARD
(Lunar and Planetary Laboratory, University of Arizona)

Figure 14. Evolution of Saturn with separation of heavy elements. Homogeneous evolutionary models are labeled “Saturn” and “Jupiter,” while the evolution of Saturn with separation of CNO elements is labeled “Saturn:Ice.”
Hypothetical phase transitions in interiors of Jupiter and Saturn
Hypothetical Phase Transitions in interiors of Solar System Giant Planets

**Neptune**
- 2000 K
- 10 GPa
- H₂O+CH₄+NH₃

**Uranus**
- 4000 K
- 300 GPa
- H-C-N-O ices

- > 5000 K
- 800 GPa
- Rocks, diamond?
More than 200 «extrasolar» giant-planets have been discovered ("Hot Jupiters")

Уже открыто более 200 «внесолнечных» планет-гигантов («горячие Юпитеры»)
Hypothetical phase transitions in outer layers of white dwarfs

He-rich layer (<10^{-2} M)

C^{6+} + O^{8+} + electrons + impurities

H-rich layer (<10^{-4} M)

Jérôme Daligault // SCCS, Moscow, 2005

^{22}\text{Ne}
Phase Transitions in Astrophysical Objects

Phase transitions in $\text{H}_2 + \text{He}$ mixture

"Helium rain" (?)
Hypothetical demixing of $\text{He}$ and $\text{H}_2$
in upper and inner layers of Jupiter and Saturn

Immiscibility gap in $\text{H}_2$/He mixture

- Low-temperature demixing of liquid $\text{H}_2$ and He in upper layer of J and S
- High-temperature demixing of ionized $\text{H}$ and He in inner layer of J and S

Phase transitions in $\text{H}_2$/He mixture

transformed from their prototypes in pure hydrogen and helium:

- hydrogen-like phase transition(s)
- helium-like phase transition(s)

Coexistence of fluid He and $\text{H}_2$

(theory vs. experiment)

Phase Transitions in Astrophysical Objects

Phase decomposition in H + He mixture

"Helium rain" (?)
Hypothetical demixing of ionized H and He in inner and upper layers of Jupiter and Saturn

Calculation of demixing boundary for H/He plasma
\{ H^+ + He^{++} + e(-) \}
via Density Functional Theory (DFT) + Mol.Dynamics:

Expected presence of «plasma phase transition» in interiors of Jupiter and Saturn


![Graph showing the expected presence of plasma phase transition in the interiors of Jupiter and Saturn.](image)
Typical picture of plasma phase transition expected in H$_2$/He mixture in interior of Jupiter and Saturn

Chabrier G., Saumon D., Hubbard W., Lunine J. (SCCS-1992, Rochester)

Fig. 1. Pressure and density profiles of optimized models of Jupiter (top panel) and Saturn (bottom panel), plotted as a function of mean radius. Discontinuities in the density clearly mark the boundaries of the four layers of the models: rocky core, ice mantle, metallic and molecular
Typical picture of plasma phase transition expected in interior of Giant Planets

**Jupiter**

**Neptune**

FIG. 2—Pressure-density relation along a pure hydrogen Jupiter adiabat ($T = 165$ K at $P = 1$ bar). The MH EOS is shown by the long dash-dot curve.

Pressure-density relations for Uranus and Neptune models, compared with theoretical curves. Dotted

**Strongly Coupled Plasma Physics**
**Int. Conference, Rochester, 1992**
Typical picture of plasma phase transition expected in interior of Giant Planets

BURROWS, HUBBARD, LUNINE and LIEBERT
The theory of brown dwarfs and extrasolar giant planets
Rev. Mod. Phys. 73, 719-769, 2001

J. FORTNEY & W. HUBBARD
Phase Separation in Giant Planets
Icarus, 164, 2003
Hypothetical “Plasma Phase Transition” in hydrogen

Relevant to the problem of Saturn and Jupiter formation

(*) Beulle, Ebeling et al. (1999)


R-2005 Redmer et al. 2005

MuK

Hypothetical Plasma Phase Transition (transitions) in helium

Ebeling, Foerster et al. (1991)

Winisdoerffer Ch., Chabrier G.,
Free-energy model for fluid helium at high density
Quantum Monte-Carlo Simulations
(V. Filinov, M. Bonits, P. Levashov, V. Fortov)

“Plasma” phase transition in hydrogen

Figure from:
V. Filinov, P. Levashov
et al.
SCCS-2005,
Moscow

$T = 10000 \text{ K, } n = 3 \cdot 10^{22} \text{ cm}^{-3}$
Theoretical prediction of “dissociative” fluid-fluid phase transition in liquid hydrogen (deuterium)

Fluid–fluid phase transition in hydrogen [*] (?)

Density Functional Theory + Molecular Dynamics

Theoretical prediction of "dissociative" fluid-fluid phase transition in liquid hydrogen

Wave Packet Molecular Dynamics (WPMD) Theory (2007)

Problem of experimental confirmation of theoretically predicted phase transitions in hydrogen
Experiments in VNIEF (Sarov)

Quasi-isoentropic compression gaseous deuterium up to the pressure 75-300 GPa

Density “jump” at isentropic compression

After: M. Mochalov et al.
SCCS-2005, Moscow

SAHA-IV: Chemical model (Gryaznov et al.) with modified Coulomb corrections and interaction parameters $H_2-H_2 / H_2-H / H-H$ – in accordance with “atom-atomic” approximation (E. Yakub – Physica B 265 31 (1999)}
Density break in isentropic compression of gaseous deuterium ⇔ hypothetical phase transition (?)

PPT – "Ionization driven" phase transition (Beule D., Ebeling W. et al. PRB, 1999)
DPT* – "Dissociation driven" phase transition (Ab Initio: WPMD // Jakob et al. 2007)

Fortov V., Mochalov M. et al. (Submitted to Phys. Rev. Lett.) // Iosilevskiy I., Gryaznov V., Fortov V. (to be published)
Hypothetical phase transition in $\text{H}_2$/He mixture ⇔ Planets evolution problem (?)

Fig. 3.—Adiabats computed from the EOS described in § 2 with a helium mass fraction $Y = 0.24$. The heavy solid line is the coexistence curve of the plasma phase transition and the critical point is indicated by a dot. Solid lines are computed from the EOS with PPT, dashed lines from the interpolated hydrogen EOS (see text). The temperature of the adiabats at the 1 bar pressure level is, from left to right: 135 (Saturn), 165 (Jupiter), 1500, and 3500 K. In a
Non-congruent phase coexistence
in uranium-oxygen plasma

Igor Iosilevskiy
Moscow Institute of Physics and Technology (State University)
Victor Gryaznov & Vladimir Fortov
Institute of Problems of Chemical Physics RAS, Chernogolovka, Russia
Eugene Yakub
Odessa State Economic University, Ukraine
Alexander Semenov
Moscow Power Engineering Institute, Russia
Claudio Ronchi
Institute for Transuranium Elements, JRC, Karlsruhe, Germany
Gerard J. Hyland
University of Warwick, Coventry, United Kingdom
Non-Congruent Phase Transition in Uranium Dioxide

Expected Temperature at Hypothetical **Severe Accident** at Fast-Breeder **Nuclear Reactor**


**Cooperation:** MIPT – IHED RAS – IPCP RAS – OSEU – MPEI ⇔ ITU (JRC, Germany)

Project Coordinator – C. Ronchi (ITU, JRC) ⇔ Project Supervisor – V. Fortov


**Cooperation:** MIPT – IHED RAS – IPCP RAS – ITEP – VNIIEF ⇔ GSI (JRC, Germany)

Project Manager – B. Sharkov (ITEP, Moscow) ⇔ Project Science Supervisor – V. Fortov
Non-congruent phase transition in uranium dioxide

Sketch of theoretical approach

Quasi-chemical representation for liquid & gaseous phases

**Ionic Model**
*(Liquid)*

\[ U^{6+} + U^{5+} + U^{4+} + U^{3+} + O^{2-} + O^- \]

**Multi-molecular Model**
*(Liquid & Gas)*

\[ U + O + O_2 + UO + UO_2 + UO_3 \]
\[ U^* + UO^+ + UO_2^+ + O^- + UO_3^- + e^- \]

**Interactions: (Pseudopotential components)**
- Intensive Short-range Repulsion
- Coulomb Interaction between Charged Particles
- Short-range Effective Attraction between all Particles

**Interaction corrections: (Modified for mixtures)**
- Hard-sphere Mixture with Varying Diameters
- Modified Mean Spherical Approximation \((MSAE+DHSE)\)
- Modified Thermodynamic Perturbation Theory \(\{TPT- \sigma(T); \varepsilon(T)\}\)


Forced-congruent evaporation in U-O system

- Stoichiometry of coexisting phases are equal: $x' = x''$
- Van der Waals loops (at $T < T_c$) corrected via the “double tangent construction”
- Standard phase equilibrium conditions:
  $$P' = P'' \parallel T' = T'' \quad G'(P,T, x) = G''(P,T, x)$$
- Standard critical point:
  $$(\partial P/\partial V)_T = 0 \parallel (\partial^2 P/\partial V^2)_T = 0 \parallel (\partial^3 P/\partial V^3)_T < 0$$
Non-congruent evaporation in U-O system

Pressure - Density Diagram

1 – Non-congruent (total) equilibrium
2 – Forced-congruent (partial) equilibrium

Pressure - Temperature Diagram

BC – Boiling (liquid) conditions
SC – Saturated (vapor) conditions

Non-congruent phase boundaries
Double-tangent construction (standard procedure)

Critical Point

NB! 2-dimensional two-phase region instead of standard P-T saturation curve

NB! High pressure level of non-congruent phase decomposition

NB! Critical point should be of non-standard type: 
\[(\partial P/\partial V)_T \neq 0 \quad (\partial^2 P/\partial V^2)_T \neq 0\]

It should be instead: 
\[(O/U)_{\text{liquid}} = (O/U)_{\text{vapor}} \quad \|\partial \mu_i/\partial n_k\|_{T, \text{cp}} = 0\]
Non-congruent evaporation in U – O system

Isotherms in Two-Phase Region

- **Isothermal** phase transition starts and finishes at *different pressures*
- **Isobaric** phase transition starts and finishes at *different temperatures*

Non-congruent evaporation in U – O system

Stoichiometry of Coexisting Phases
(two limits)

Boiling Conditions
Liquid (O/U = 2.0) ⇔ Vapor (O/U > 2.0)

First vapor bubbles over the boiling UO$_{2.0}$
(oxygen enriched)

Saturation Conditions
Vapor (O/U = 2.0) ⇔ Liquid (O/U < 2.0)

First liquid drops in vapor UO$_{2.0}$
(“dew point”)

NB! High oxygen enrichment of vapor over the boiling UO(2.0)
Main issue of study of non-congruent evaporation in U – O system

Non-congruence of phase transition in U-O system –
– is it an exclusion or a general rule?

Basic conclusion
– Any phase transition in a system of **two or more chemical elements** must be **non-congruent**.
– Congruent phase transitions are exclusion.

• **Hypothetical example of non-congruent phase transition**
  • “Plasma Phase Transition” (PPT) in H₂/He mixture in *Jupiter*, *Saturn* (GP), *brown dwarfs* (BD) and *extra-solar giant planets* (EGP).
Non-congruent phase transitions in astrophysical objects

Neptune

Water (Phase Diagram*)

Pressure P (Mbar)

Temperature T (eV)

Solid

Superionic

Ionic Fluid

Metallic

Molecular

(*) C. Cavazzoni et al., 1999
Hypothetical **non-congruent** plasma phase transition in \((H_2 + He)\) mixture in interiors of Jupiter and Saturn

**NB!**

Two-phase region in H2/He must be non-conventional **two-dimensional** domain instead of one-dimensional curve

**Estimated non-congruence for plasma phase transition in H₂/He mixture of Jupiter and Saturn**

*(PPT-variant of Saumon, Chabrier and Van Horn – 1995)*

**Phase Separation in Giant Planets:**
Jonathan J. FORTNEY, William B. HUBBARD
Icarus, 164 (1) 2003

**Atmospheric elemental abundances in Jupiter and Saturn**
*(mass fractions)*

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* Результаты оценки гипотетической неконгруэнтности ПФП в версии Saumon & Chabrier оправдывают **полномерный расчет** этого эффекта.

- Это справедливо для **всех вариантов** гипотетических фазовых переходов, предсказываемых в чистом водороде и гелии, когда эти ФП переносятся в смесь H₂/He.
Estimated non-congruence for plasma phase transition in \( \text{H}_2/\text{He} \) mixture of Jupiter and Saturn

(PPT-variant of Saumon, Chabrier and Van Horn – 1995)

Assumptions:
- Helium is not ionized.
- Atomic helium interacts with neutral hydrogen species only (\( \text{H}_2 \) and H).
- Interaction of atomic helium with charged species are low and repulsive.

A. Ukrainets & I. Iosilevskiy
in “Physics of matter under extreme conditions”,
Ed. V.Fortov, Moscow, IPCP (2005) 116. (in Russ.)
Assume we know thermodynamics of pure H\textsubscript{2} and He: How could we obtain the thermodynamics of H\textsubscript{2} + He mixture?

"Additivity approximation" is widely used for this purpose:

\[
\text{EOS } (H_2 + \text{He}) = x_{H_2} \text{EOS}(H_2) + (1 - x_{H_2}) \text{EOS}(\text{He})
\]

**Main issue for the phase transition problem**

\[
(\frac{\partial V_A}{\partial P})_T = \infty \quad \Rightarrow \quad (\frac{\partial V_{(A+B)}}{\partial P})_T = \infty
\]

**Critical point(s) and (P,T)-coexistence curve(s) of PT(s) in H\textsubscript{2}/He mixture are the same identically as those of phase transition(s) in pure H\textsubscript{2} and He**

**Conclusion:**
P-T phase diagram of H\textsubscript{2}/He mixture in frames of "additivity approximation" is superposition of P-T phase diagrams of pure hydrogen and helium.
Hypothetical phase transitions in interiors of GP-s and BD-s via “additivity approximation”

Phase diagram of H\(_2\)/He mixture in frames of ‘additivity approximation’ is **superposition** of P-T phase diagrams for pure hydrogen and helium.

**Dissociative Phase Transition in H\(_2\)**
*(Scandolo S., Bonev S., Militzer B., Galli G.)*

**Plasma Phase Transition in H**
*(Ebeling et al.)*

**1\(^{st}\) Plasma Phase Transition in He**
*(Ebeling et al.)*

**2\(^{nd}\) Plasma Phase Transition in He**
*(Ebeling et al.)*

Presence of helium relax phase transition in hydrogen <=> presence of hydrogen relax phase transition in helium

Thermodynamics of $\text{H}_2 + \text{He}$ plasma


Plasma Phase Transition in Fluid Hydrogen-Helium Mixtures

M. Schlanges (a), M. Bonitz (b), and A. Tschitschjan (b)
Thermodynamics of (H₂ + He) plasma

(continued)

Fig. 7. Coexistence pressure for H—He mixtures for different values of the mixing parameter, for the hydrogen-like plasma phase transition and for the helium-like plasma phase transition.
Elemental Abundance in Solar and Extrasolar Planets

FIG. 10. A plot of the abundance of the elements vs atomic number. The position of the element name indicates its elemental abundance according to Anders and Grevesse (1989); see Table II. The balloons contain representative associated molecules/atoms/condensates of importance in brown dwarf and giant planet atmospheres. See Sec. V in text for discussion [Color].

Parameters of the Models of Saturn

<table>
<thead>
<tr>
<th>Model</th>
<th>$Y_1$</th>
<th>$Y_2$</th>
<th>$Z_{2-4}$</th>
<th>$P_m$</th>
<th>$P_{1-2}$</th>
<th>$M_{\text{H}_2, \text{core}}$</th>
<th>$M_{\text{core}}$</th>
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<tbody>
<tr>
<td>MS1</td>
<td>0.267</td>
<td>0.06</td>
<td>0.30</td>
<td>3.0</td>
<td>0.42</td>
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<td>8.59</td>
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<td>0.44</td>
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<td>0.30</td>
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<tr>
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<td>0.30</td>
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<tr>
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<td>3.0</td>
<td>0.49</td>
<td>3.80</td>
<td>6.38</td>
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<td>MS11</td>
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<td>0.30</td>
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<td>0.41</td>
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<td>MS12</td>
<td>0.293</td>
<td>0.35</td>
<td>2.0</td>
<td>0.48</td>
<td>3.90</td>
<td>6.15</td>
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<tr>
<td>MS13</td>
<td>0.255</td>
<td>0.30</td>
<td>0.0</td>
<td>0.62</td>
<td>0.81</td>
<td>2.11</td>
<td></td>
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<tr>
<td>MS14</td>
<td>0.282</td>
<td>0.30</td>
<td>1.5</td>
<td>0.60</td>
<td>2.60</td>
<td>4.42</td>
<td></td>
</tr>
<tr>
<td>MS15</td>
<td>0.249</td>
<td>0.30</td>
<td>1.5</td>
<td>0.75</td>
<td>0.007</td>
<td>0.76</td>
<td></td>
</tr>
</tbody>
</table>

$Y_1 = 0.06, Y_2 = 0.25, Z = 0.04, I/R = 2.2$

I - “Ices” (H$_2$O, NH$_3$, CH$_4$)
R - rocks + Fe + Ni
Y - весовая доля гелия
Z$_G$ - весовая доля {H$_2$O, NH$_3$, CH$_4$ + Fe + Ni}
Optimized models of Jupiter and Saturn

<table>
<thead>
<tr>
<th></th>
<th>JUPITER</th>
<th>SATURN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ ($\oplus$)</td>
<td>317.7</td>
<td>95.1</td>
</tr>
<tr>
<td>$M_\oplus$ ($\oplus$)</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>$M_{i\text{io}}/M_\oplus$</td>
<td>0.50</td>
<td>0.95</td>
</tr>
<tr>
<td>$P_c$ (Mbar)</td>
<td>67.4</td>
<td>15.5</td>
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<tr>
<td>$T_c$ (K)</td>
<td>22600</td>
<td>11900</td>
</tr>
<tr>
<td>$P_{PPT}$ (Mbar)</td>
<td>1.71</td>
<td>1.93</td>
</tr>
<tr>
<td>$T_{PPT}$ (K)</td>
<td>6880</td>
<td>6070</td>
</tr>
<tr>
<td>$Y_I$</td>
<td>0.29</td>
<td>0.25</td>
</tr>
<tr>
<td>$Y_{II}$</td>
<td>0.326</td>
<td>0.73</td>
</tr>
</tbody>
</table>

TABLE 1
Optimized models of Jupiter and Saturn

GIANT PLANETS AND THE PLASMA PHASE TRANSITION OF HYDROGEN
D. Saumon, G. Chabrier, W. B. Hubbard, and J. I. Lunine  111
Giant planets interior composition
(After N. Nettelmann, R. Redmer, et al., PNP-12, Darmstadt, 2006)

Saturn interior composition using SCVH-95_EOS

(H₂ + He) Saumon, Chabrier & VanHorn (1995)

Neptune interior composition using Sesame-EOS (G.Kerley, LANL)

(H₂, He, H₂O) EOS from Sesame-EOS-Tables
H₂O phases from DFT-QMD: T. Mattsson
Conclusions and perspectives

- Non-congruence of phase transitions in H$_2$/He mixture can ‘provoke’ to the H$\Leftrightarrow$He separation in interiors of jovian and extrasolar planets and brown dwarfs.

- First estimation of non-congruence for SCVH-variant of plasma phase transition in H$_2$/He mixture approves considering of non-congruence in study of helium sedimentation in interiors of Jupiter and Saturn.

- *Ab initio* approaches are very promising for direct numerical simulation of discussed non-congruence for phase transitions in H$_2$/He mixture in conditions of jovian and extrasolar planets and brown dwarfs.

- New experiments are desirable for study of discussed non-congruence for phase transition in H$_2$/He mixture under conditions of jovian and extrasolar planets and brown dwarfs.
Clearly there will be enough challenges
to keep us all happily occupied for years to come.

Hugh Van Horn (1990)
(Phase Transitions in Dense Astrophysical Plasmas)

Thank you!
Thank you!

![Graph showing melting point of UO₂ as a function of temperature and pressure.]

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