Interior structure and magnetic fields

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Outline

Interior structure
- What data do we have?
- How to construct interior structure models

Magnetic fields
- What data do we have?
- Necessary conditions for dynamo generation
### Planetary Data

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**Density** \[\rho [\text{kg/m}^3]\]
Interior structure and composition

- Mass of reservoirs (crust, mantle, core)
- Composition (rheology)
- Depth of phase transitions and chemical layers
- Variation of pressure, temperature and density
Data

- Mass, Radius
- Gravity field, rotational state
- Chemistry / mineralogy of the surface
- Cosmochemical data (e.g. SNC meteorites, Moon rocks)
- Data from the laboratory
- Seismic data
- Heat flow
Gravitational potential

Reference radius of coefficients

Low degree → large scale density distribution (crust, mantle, core)

\[ U(r, \theta, \phi) = \frac{GM}{r} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \left( \frac{R_0}{r} \right)^l C_{lm} Y_{lm}(\theta, \phi) \]

Spherical Harmonic function

Spherical Harmonic Coefficient

\[ J_2 MR_2 = C - \frac{(A + B)}{2} \]
Precession constant

\[
H = \frac{C - \frac{(A + B)}{2}}{C}
\]

Radau-Darwin-Relation for hydrostatic compensated planets

\[
\frac{C}{MR^2} = \frac{2}{3} \left[ 1 - \frac{2}{5} \left( \frac{4m - 3J_2}{m + 3J_2} \right) \right]
\]

\[
m = \frac{\omega^2 R^3}{GM}
\]

rotation parameter
Simple Two-Layer Model

\[ M = \frac{4}{3} \pi \left( R_P^3 - R_c^3 \right) \rho_m + R_c^3 \rho_c \]

\[ \frac{I}{MR_P^2} = \frac{2}{5} \left( 1 - \left( \frac{R_c}{R_P} \right)^5 \right) \left( \frac{\rho_m}{\bar{\rho}} \right) + \left( \frac{R_c}{R_P} \right)^5 \left( \frac{\rho_c}{\bar{\rho}} \right) \]

\[ \frac{I}{MR_P^2} = \frac{C}{MR_P^2} - \frac{2}{3} J^2 \]
2 knows:
M  mass
I  moment of inertia

3 unknowns:
R_c  core radius
\( \rho_m \)  mantle density
\( \rho_c \)  core density
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Detailed Models of the Interior

**Structural Equations**

mass, $m$

\[
\frac{dm}{dr} = 4\pi r^2 \rho
\]

moment of inertia, $\theta$

\[
\frac{d\theta}{dr} = \frac{8}{3} \pi r^4 \rho
\]

gravity, $g$

\[
\frac{dg}{dr} = 4\pi G \rho - 2 \frac{g}{r}
\]

pressure, $p$

\[
\frac{dp}{dr} = -g \rho
\]

Model assumptions:

- Spherically symmetric and fully differentiated planets
- Hydrostatic and thermal equilibrium
Equation of State

- Relates local density $\rho (p, T)$ to ambient pressure $p$ and temperature $T$.
- Linear thermal pressure correction (1).
- Isothermal compression (2).

\[ p = \frac{3K_0T}{2} \left[ \left( \frac{\rho}{\rho_0} \right)^{7/3} - \left( \frac{\rho}{\rho_0} \right)^{5/3} \right] \left\{ 1 + \frac{3}{4} (K'_0 - 4) \left[ \left( \frac{\rho}{\rho_0} \right)^{2/3} - 1 \right] \right\} + \alpha_0 K_0 T (T - 298) \]
Typical Temperature profile

- $r_p$: outer boundary of the mantle
- $d$: depth of the mantle
- $r_c$: radius of the fluid outer core
- $d_{um}$: thickness of the stagnant lid
- $\delta_{cm}$: thickness of the outer core
- $r_{icb}$: radius of the inner core boundary
- $T_s$: surface temperature
- $T_l$: temperature at the base of the stagnant lid
- $T_m$: temperature at the top of the fluid outer core
- $T_c$: core temperature
- $T_{cmb}$: temperature at the core-mantle boundary
- $T_{mel}$: melting temperature
- Solid inner core
- Fluid outer core
- Stagnant lid

The graph illustrates the typical temperature profile through the Earth's layers, highlighting the transition zones and temperature changes.
Interior Structure of Mars

Sohl und Spohn, 1997
Earth and Mars in comparison
Sohl and Spohn, 1997

Mars Interior Structure

FeS

15 weight-% S

Fe

Perovskite

MoI=0.3662

Sohl and Spohn, 1997
Perovskite layer thickness near core/mantle boundary dependent on lower mantle temperature

- Mantle
- Core
- Perovskite layer
- No perovskite layer
- \( \frac{dP}{dT} \approx 3 \text{ MPa/K} \)
Why are phase transitions interesting?

- Influence on the mantle dynamics and thermal structure
Influence of phase transition on mantle dynamics

without PT

time

with PT

time

Buske 2008
The Crust

Mars

The Moon

Neumann et al. (2004)

GRAIL Crustal Thickness

Wieczorek et al. (2013)
Assume crust and mantle density and average crustal thickness.

Free-air gravity anomaly is a result of relief along the surface, and crust-mantle interface.

Calculate Bouguer correction. This is the gravitational attraction of relief along the surface. Subtracting this from the free-air gravity gives the Bouguer anomaly.

Assume that the Bouguer anomaly is the result of relief along the crust-mantle interface.
Lateral Density Variations in the Crustal layer?

- uniform density $\rho_c$ of both hemispheres. The crustal dichotomy is compensated by Airy isostasy.

- crustal density variation with the density of southern highland crust lower than the density of northern lowland crust. The compensation mechanism in this case is Pratt isostasy.

- crustal density variation with the density of southern highland crust higher than the density of northern lowland crust.
How to constrain crustal density?

- Density of the crust can be also constrained by high order gravity field (not influenced by elastic thickness)

- For the “right“ density, observed gravity is equal to Bouguer correction and measurement noise

- Minimizing correlation between Bouguer anomaly and topography

- Moon: crustal density indicates on high porosity
Magnetic Field Generation
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Present dynamo: ❌ - ❌ - - ❌ - ❌
Mercury

- Weak field
- Low dipole tilt
- Dipole is offset to the North by 20% of the planetary radius (strong quadrupole contribution)
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**Present dynamo**:  
- Mercury: ?  
- Venus: -  
- Earth: -  
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- Ganymede: ?  
- Io: -

**Early dynamo**:  
- Mercury: ?  
- Venus: ?  
- Earth: -  
- Mars: -  
- Moon: ?  
- Ganymede: ?  
- Io: ?
Origin of Remanent Magnetization

- Thermal remanent magnetization (TRM)
  - If a magnetic mineral is cooled in an ambient magnetic field through a temperature characteristic of the material, Curie temperature, it will begin to acquire a large remanent magnetization.

  Magnetite  ~ 853 K
  Hematite    ~ 953 K
  Iron        ~ 1043 K
Remanent Crust Magnetization

- Magnetized crust provides information about
  - History of the magnetic field
  - Geological and tectonic processes

Acuna et al., 1999
Magnetic Field Generation

⇒ Necessary conditions for existence

⇒ A conducting fluid
⇒ Motion in that fluid
⇒ Cowling’s Theorem requires some helicity in the fluid motion
Dynamos

- Hydromagnetic dynamos
  - Driven by thermal buoyancy
  - Driven by chemical buoyancy
- Thermoelectric dynamo

Dietrich & Wicht 2013
Dynamo model for Mars
Thermal dynamo

- Fluid motion in the liquid iron core due to thermal buoyancy (=> cooling from above)
- ‘Critical‘ heat flow out of the core
Thermal Evolution of the Martian Core

Breuer and Spohn, 2003
Thermal Dynamo

- Thermal dynamo only likely in the early evolution (~ few hundred million years)
- Core most likely needs to be superheated with respect to the mantle
  - Rapid core formation necessary?
Chemical Dynamo

- Compositional buoyancy released by inner core growth

- Difficult to stop operating
Chemical Dynamo

- Existence of light alloying elements in the core like S, O, Si
- Core temperature between solidus and liquidus
Magnetic field evolution with a growing inner core

Thermal  Chemical

Difficult to stop operating
Magnetic field depending on composition and heat transport

Fluid core

Light elements in the core

Inner core growth
Magnetic field generation

Efficiency of mantle cooling

Stagnant lid
Plate tectonics

$t_1$
Magnetic field depending on composition and heat transport

- Inner core growth
- Magnetic field generation
- Fluid core
- Large inner core
- Weak magnetic field?
- Efficiency of mantle cooling
- Stagnant lid
- Plate tectonics
- Light elements in the core
- Mars
- Venus
- Mercury
- Earth
- Magnetic field depending on composition and heat transport
Later in time ....

- Inner core growth
- Magnetic field generation
- Fluid core
- Solid core
- No magnetic field
- Stagnant lid
- Plate tectonics
- Light elements in the core
- Efficiency of mantle cooling
- Mars
- Venus
- Earth
- Mercury
- Large inner core
- Weak magnetic field?
Fig. 4. Pressure dependence of the eutectic temperature of the Fe-rich portion of the Fe–S system (see Table 1). Observations from recovery experiments: solid squares – no melt features; mixed symbols – melt features together with solid phases; open squares: mainly quench textures recrystallized from liquid. Open circles: melting observed by in situ laser-speckle method. Solid line is the present solidus boundary. Dashed lines are previous eutectic measurements: Ryzhenko and Kennedy [4], Usselman [5], Williams and Jeanloz [11], Boehler [10], Fei et al. [6–8]. The iron melting curve is from Boehler [9].
Fig. 5. Pressure dependence of Fe–FeS eutectic composition (wt.% S) measured by SEM EDX analysis in runs 5 (rim), 12, and 10 (see Table 1); our data are shown by circles, previous data are shown by diamonds [5] and squares [6–8].
‘Classical’ Earth

Chemical Dynamo

Liquid outer core
(Fe-FeS)

Solid inner core
(Fe)

Mantle
Core
T
T_profile
P

core liquidus
core liquidus

Temperature / °C

Fe + Schmelze
FeS
Schmelze

Fe + FeS

Massenanteil FeS/%
Iron snow may form a solid inner core or remelt upon sinking (chemical iron gradient)
Low Pressure Chemical Dynamo

Fe-snow

Magnetic field generation in lower fluid core

No dynamo
Magnetic field depending on composition and heat transport (for iron snow)

- Fluid core
- Efficiency of mantle cooling
- Stagnant lid
- Plate tectonics
- Iron snow with lower fluid core
- Magnetic field generation
- Light elements in the core
- $t_1$
Magnetic field depending on composition and heat transport (for iron snow)

- Iron snow (with lower fluid core)
- Magnetic field generation
- Fluid core
- Iron snow with solid inner core, no magnetic field?
- Efficiency of mantle cooling
- Stagnant lid, Plate tectonics
- Light elements in the core
- Mars, Mercury
- Magnetic field depending on composition and heat transport (for iron snow)
Absence of a present-day dynamo suggests either ...

- Entirely fluid core which does not convect
- Inner core in the iron snow regime
- Solid core (difficult to get during the last 4.5 Ga)
- Inner core that stopped to grow
  - Core ceased to cool (possible only during a short period)
What future geophysical data are required to better constrain the interior structure and magnetic fields?

> I have learned that it is your business to think about it …