SCIENCE OF EXTREME CONDITIONS:

The Legacy of Erskine Douglas Williamson

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Erskine Douglas Williamson (1886-1923)
Erskine Douglas Williamson: Chronology

1886 Born April 10, Scotland
1908 B. S., Univ. of Edinburgh
1909 M. A., Univ. of Edinburgh
1909 Carnegie Trust of Scotland
1914 Geophysical Laboratory, Carnegie Institution
1918 Married Alice Boorman
1923 Died Dec. 25, Washington, D.C.

A LEGACY OF RESEARCH

1914-16 Formation of carbonate rocks
   Thermodynamics, new phases, geology
1916-22 Fabrication of optical glass
   Annealing, heat flow, thermodynamics
1918-19 Thermodynamic theory
   Heterogeneous equilibria, effects of strain
1918-22 High-pressure experimentation
   Compressibility, elasticity, viscosity, conduct.
1922-23 Nature of the Earth’s interior
   Pressure-density relations; mantle and core
Density Distribution in the Earth

E. D. WILLIAMSON AND L. H. ADAMS

Reprinted from Journal of the Washington Academy of Sciences, Vol. 13, No. 19, November 19, 1923

\[
\frac{d\rho}{dr} = -\frac{GM_r\rho(r)}{r^2(\alpha^2 - \frac{4}{3}\beta^2)} = -\frac{GM_r\rho(r)}{r^2\Phi}
\]

\[
\alpha = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \quad \beta = \frac{\mu}{\sqrt{\rho}}
\]
PRESSURES INSIDE THE EARTH

\[ \frac{d\rho}{dr} = -\frac{GM_r \rho(r)}{r^2(\alpha^2 - \frac{4}{3} \beta^2)} = -\frac{GM_r \rho(r)}{r^2 \Phi} \]

\[ \alpha = \sqrt{\frac{K + \frac{4}{3} \mu}{\rho}} \quad \beta = \sqrt{\frac{\mu}{\rho}} \]

10^3 \text{ atm } \approx \text{ kbar}
10^6 \text{ atm } \approx \text{ Mbar}
10 \text{ kbar } = 1 \text{ GPa}
1 \text{ Mbar } = 100 \text{ GPa}
RANGE OF PRESSURE IN THE UNIVERSE

<table>
<thead>
<tr>
<th>Pressure (Atmospheres)</th>
<th>Hydrogen gas in intergalactic space</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interplanetary space</td>
</tr>
<tr>
<td></td>
<td>Atmosphere at 300 miles</td>
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<tr>
<td></td>
<td>Center of Jupiter</td>
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<td></td>
<td>Center of Sun</td>
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<tr>
<td></td>
<td>Center of white dwarf</td>
</tr>
<tr>
<td></td>
<td>Center of neutron star</td>
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</tbody>
</table>

- Best mechanical pump vacuum
- Water vapor at triple point
- Atmospheric pressure (sea level)
- Deepest ocean
- Center of the Earth
"The variable $\mu$, which bears to the mass of a component the same relation that pressure bears to volume, temperature to entropy, or electrical potential to quantity of electricity is what we call the ‘chemical potential’.”

$$dG = -SdT + VdP + \sum \mu_i n_i$$

E. D. Williamson and G. W. Morey
“The Laws of Chemical Equilibrium”
*J. Am. Chem. Soc.* 40, 49 (1918)

**P-T CONDITIONS NOW ACCESSIBLE**

**FREE ENERGY CHANGES EXCEED BOND STRENGTHS**

[Hemley and Ashcroft (1998)]
“The difficulties of making exact measurements of any physical quantity whatever under the conditions outlined are very considerable and much time is consumed merely devising tools for the enterprise.”

“The least compressible material known is diamond. . .”

E. D. Williamson, J. Franklin Inst. 193, 491 (1922).
"X-ray analysis has elucidated the arrangement of the atoms in many of the simple crystals so that compressibility [studied in this way] should give some idea for the laws governing the forces of attraction or repulsion . . . The change in compressibility has not been examined from this point of view, so far as I know."

E. D. Williamson

*J. Franklin Inst.* 193, 491 (1922).

**"WEIRD" METALS**

*Incommensurate host-guest structures*

[McMahon et al. (2000)]
1. Condensed Matter Physics

**INSULATOR-METAL TRANSITION**

Dense plasma: ultimate fate of materials

Bernal (1926); Fowler (1927); Bridgman (1927)

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**Periodic Table of Superconductors**

![Periodic Table of Superconductors](image)

**NOVEL SUPERCONDUCTORS**

(e.g., 23 elements; O, S, B, Fe, Li)

[Shimizu et al. (2002); Struzhkin et al. (2002)]

**HIGHEST $T_c$ (164 K at 30 GPa)**

HgBa$_2$Ca$_2$Cu$_3$O$_{8+d}$

[Gao et al., (1994); Lokshin et al. (2002)]
1. Condensed Matter Physics

HYDROGEN UNDER EXTREME P-T CONDITIONS

- Molecules persist over a broad $P-T$ range
- Predicted high-$P$, low-$T$ metallic fluid
- Liquid ground state? High-$T_c$ superconductor?

**Graph:**
- Temperature (K) vs. Pressure (GPa)
- Phases: molecular solid, molecular fluid, nonmolecular fluid, shocked metal

**Experiments:**
- Static
- Dynamic
- Theory
2. Chemistry

POLYMERIC MATERIALS

CO₂

[Yoo et al. (1999)]

DIRECT MEASURE OF BONDING CHANGES
Inelastic X-ray Scattering

Transformation to Superhard Graphite

[Maó et al. (2003)]

VAN DER WAALS COMPOUNDS AND NOVEL CLATHRATES

[Somayazulu et al. (1996); Loveday et al. (2001)]
EARTHQUAKE PREDICTION:
Crack-mediated stress
dependence of elastic constants
[Silver (2004)]

“The seismological data seem to indicate
that the crust of the Earth is largely granitic
in character but at a depth of 100 km or less
basic material becomes more predominant.”

L. H. Adams and E. D. Williamson,
“Composition of the Earth’s Interior”
Smithsonian Report, 231 (1923)
3. Earth and Planetary Science

Earth’s Mantle
[Ringwood (1975); Bina (1998)]

- Pressure-induced electronic transitions
- “Invisible” boundaries within the mantle?
- Evidence for a post-perovskite phases?
Beyond reasonable doubt, the earth has a metallic core of iron or iron-nickel, the diameter being about half the earth.”

E. D. Williamson and L. H. Adams

*J. Wash. Acad. Sci.* 13, 413 (1923)

\[ T_m \sim 5800 \text{ K} \]

330 GPa

(INNER CORE BOUNDARY)

Fe Texture at 220 GPa

[Wenk *et al.* (2001); Merkel *et al.*, in press]
3. Earth and Planetary Science

EARTH DYNAMO SIMULATIONS
Magnetic Reversals

\[ \frac{d\rho}{dr} = -\frac{GM_r\rho(r)}{r^2(\alpha^2 - \frac{4}{3}\beta^2)} = -\frac{GM_r\rho(r)}{r^2\Phi} \]

Dipole Colatitude and Strength at CMB
Helicity

\[ t=3.502E-02 \text{ (frame 0)} \]

\[ t=7.005E-01 \text{ (frame 0)} \]

JOVIAN SIMULATIONS
Zonal Flows

[Olson (2003)]
4. Biology and Biochemistry

• **STRUCTURE-FUNCTION RELATIONS**

Single-Crystal Diffraction of Cow Pea Mosaic Virus

3.4 kbar
[Lin et al., to be published]

Bacteria at 14 kbar
[Sharma et al. (2002)]

Lysozyme
[Fourme et al. (2002)]

- **BIOCHEMICAL REACTIONS IN HYDROTHERMAL FLUIDS**
- **LIFE IN EXTREME ENVIRONMENTS (>10 kbar)**
4. Biology and Biochemistry

Shewanella MR1 cell replication after exposure to 14 kbar

[Sharma et al., to be published]

- *In situ* maging of single cells under stress
- “Test-tube” study of microbial evolution and adaptation
- High-pressure molecular biology
Next Generation Techniques
Towards $TPa$ Pressures with Large Volume Anvil Cells

New Radiation Sources
- Photon Sources
  - New facilities
  - Free electron lasers

- New Spallation Neutron Sources
  - Inelastic neutron/x-ray scattering
  - Time dependent (<ps-scale) diffraction
  - Heterogeneous materials: nm-diffraction
  - Interfaces/grain boundaries
  - New domains of $P-T-H-t$

Growth of Diamond Anvils by Homoepitaxial Chemical Vapor Deposition
[Yan et al. (2004)]
Generating Still Higher Pressures

Combined Anvil-Cell Laser Shock Techniques

Metallization of Fluid $H_2O$
Vulcan (RAL)
[Lee et al., to be published]

1 Gbar (100 TPa) Pressures possible
“The late Professor Tait wrote: ‘It is greatly to be desired that more and more accurate data should be obtained in the matter.’ Rather less than twenty years have elapsed since Tait died. With sufficient care and patience, a degree of accuracy may be reached which is beyond what he dreamt of.”

E. D. Williamson
J. Franklin Inst. 193, 491 (1922)

“. . . although his work was carried on far from home and country, it is nevertheless a splendid structure built for the future and certain to be productive for years to come.”
