Towards a mineral-physics reference model for the Moon's core

Daniele Antonangeli

Institut de Minéralogie, de Physique des Matériaux et de Cosmochimie
(IMPMC)
UMR CNRS 7590, Sorbonne Universités – UPMC Univ. Paris 6,
Muséum National d'Histoire Naturelle, IRD

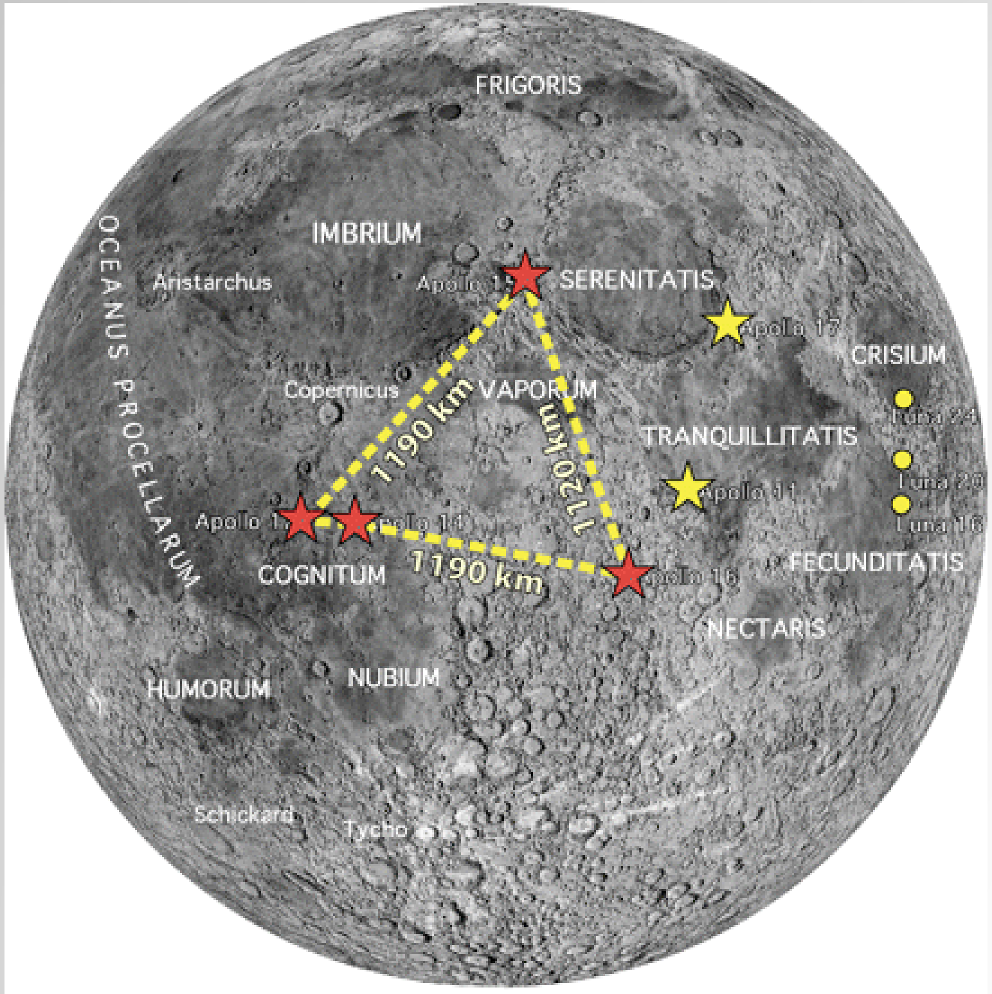
The Moon


APOLLO
NASA


AS-201
AS-203
AS-202
Apollo 4
AS-204
Apollo 6

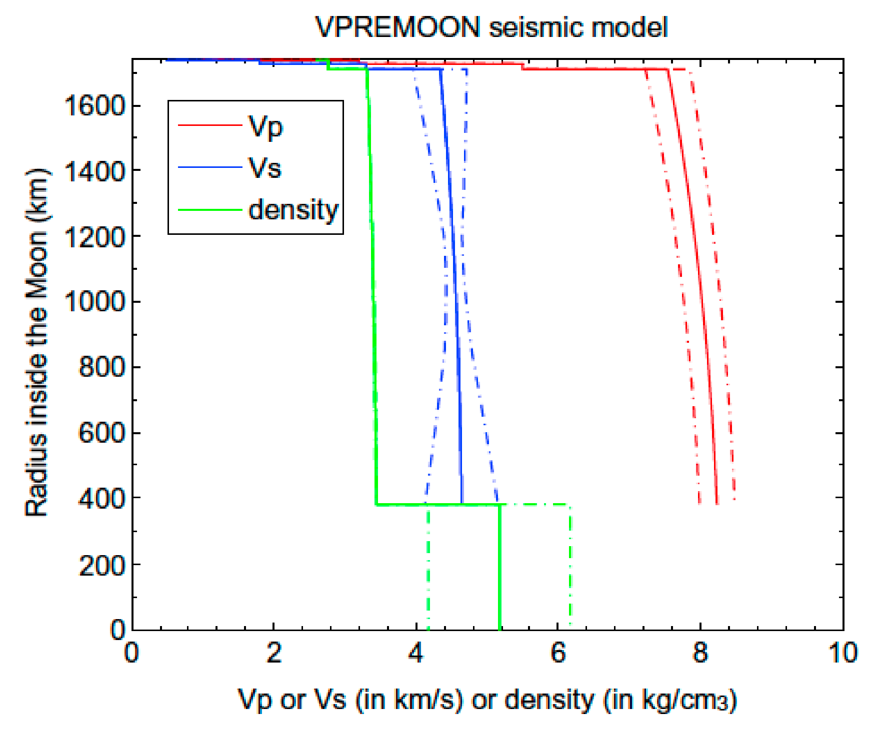

NASA
JPL
MIT
GSFC
LMSSC
SRS
GRAIL
GRAVITY RECOVERY AND INTERIOR LABORATORY

Moon seismology:
the Apollo Lunar Surface Experiments Package

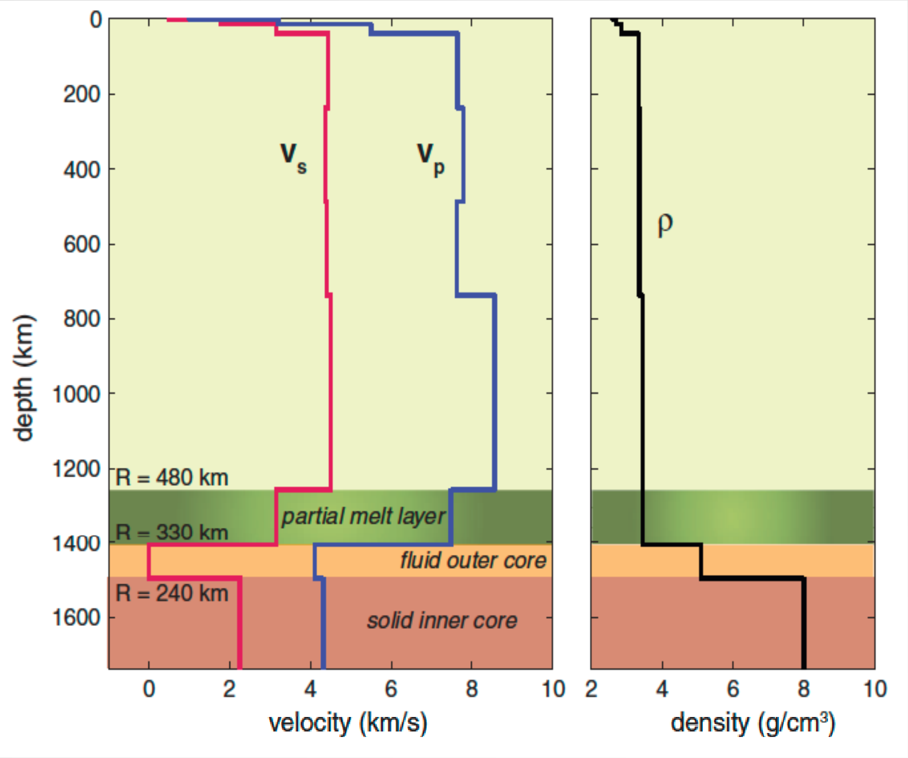


after Wieczorek et al., Elements 2009

Moon’s seismic models



Garcia et al., PEPI 2011



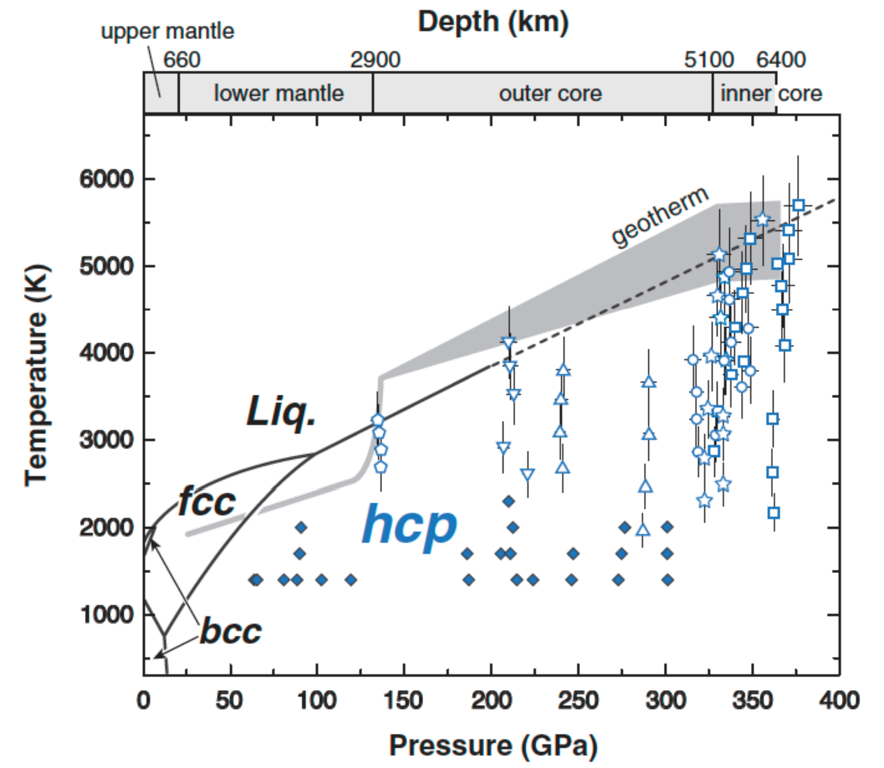
Weber et al., Science 2011

seismic investigation of the deepest lunar structures (> 900 km depth) remains very challenging

→ mineral physics constraints

→ density and sound velocities:
the link between seismic observations and models

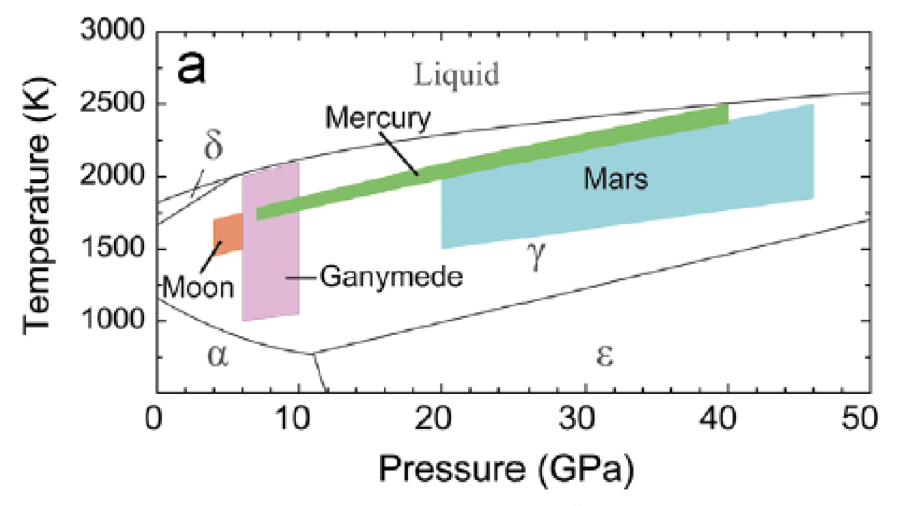
Iron phase diagram vs. planetary cores P-T conditions



Tateno et al., Science 2010

hcp (or ε) structure stable
at Earth's core P-T conditions

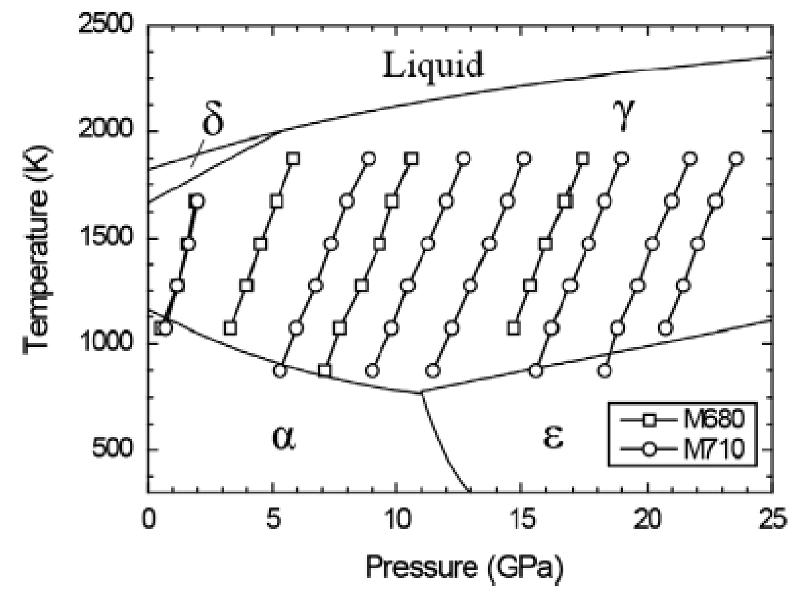
fcc (or γ) structure stable
at P-T conditions of cores
of small telluric planets and satellites



Tsujino et al., EPSL 2013

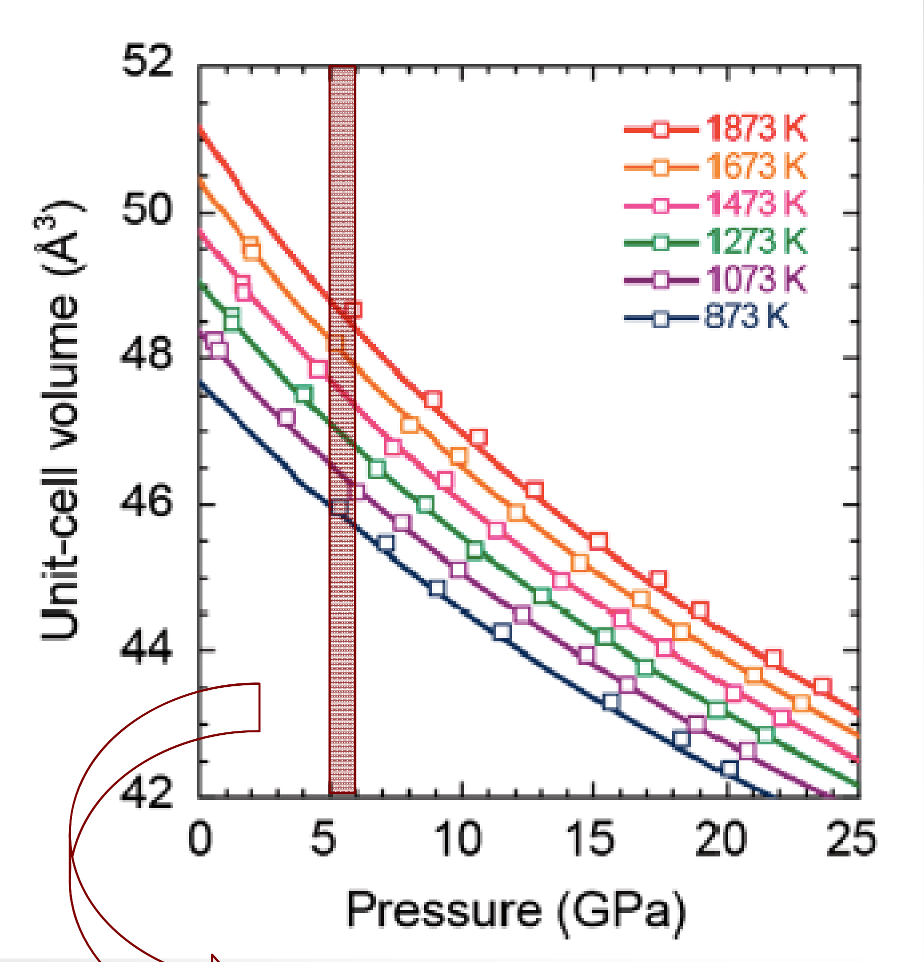
fcc-iron EOS

XRD in combination with multi-anvil press



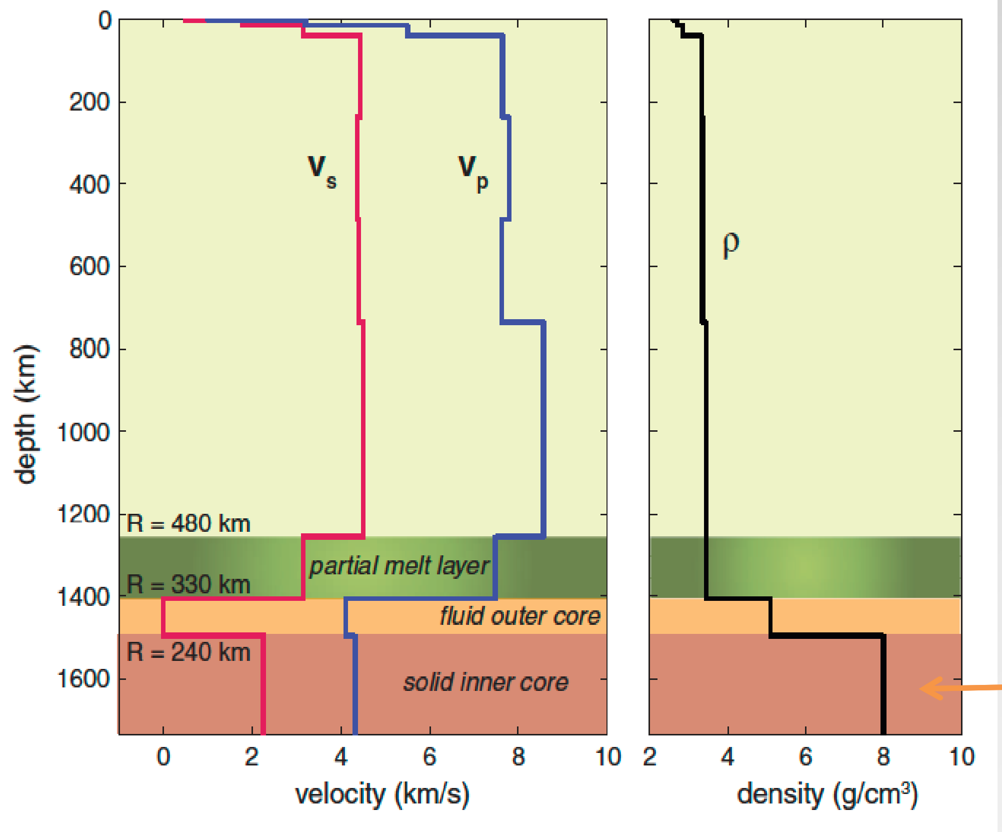
Tsujino et al., EPSL 2013

+ thermodynamic constraints
(metallurgy, phase relations)



P-V-T relations
at Moon's conditions

First checks on recent seismic models

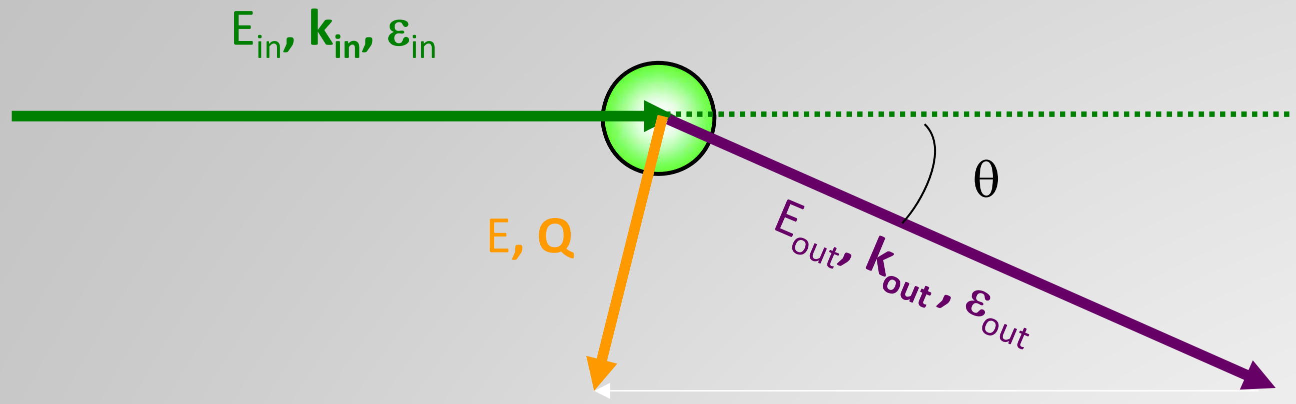


Weber et al., Science 2011

P-V-T relations
→ density 7.6-7.8 g/cm^3

What about sound velocities?

Inelastic X-ray Scattering (IXS)



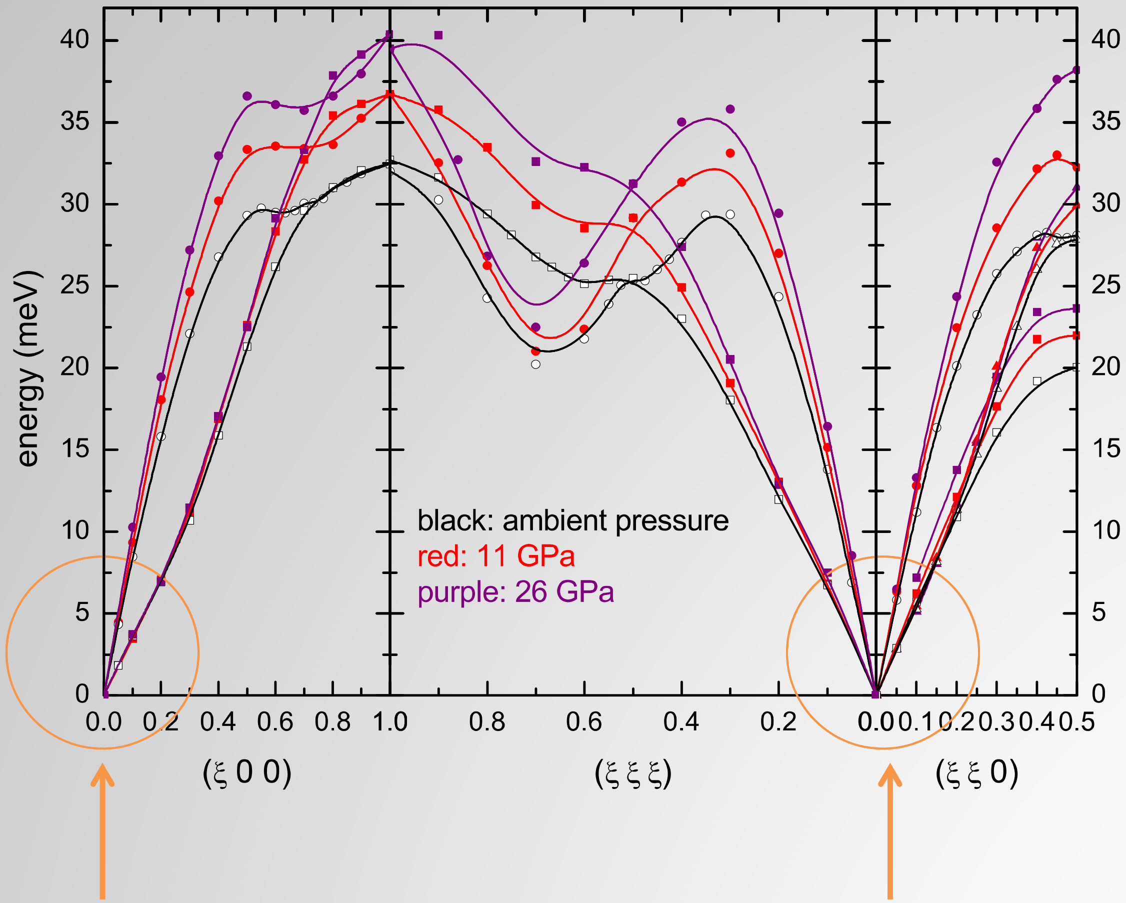
- Energy transfer $E = E_{out} - E_{in}$ $(E \ll E_{in})$ $\Downarrow$
- Momentum transfer $Q = k_{out} - k_{in} = 2k \sin(\theta/2)$ $(k_{out} \approx k_{in} \equiv k)$

◆ Directional analysis of the scattered photons $\Longrightarrow$ Q

◆ Energy analysis of the scattered photons $\Longrightarrow$ E

Phonon dispersion curves and elasticity

Ex. bcc-V at HP



Sound velocity from initial slope of acoustic modes

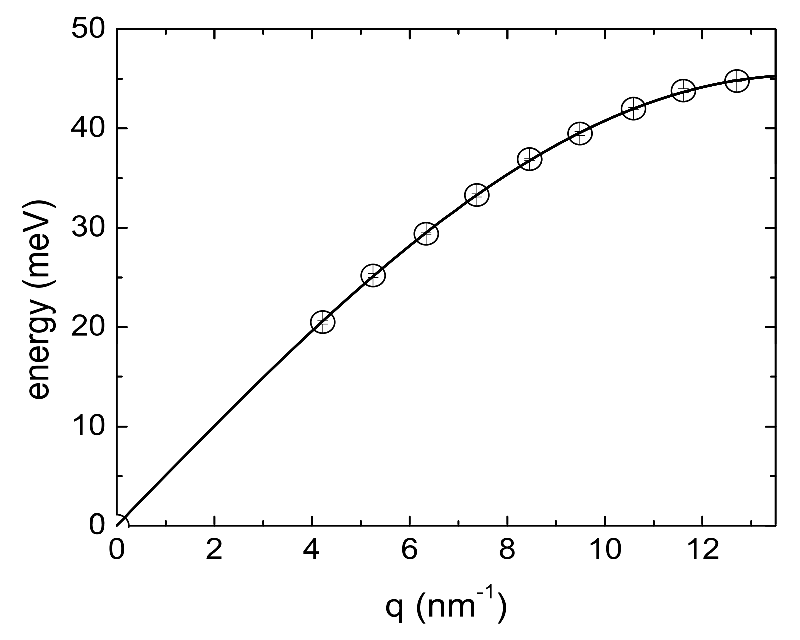
Elastic moduli C_{ij} from Christoffel equation $(C_{ijkl}n_jn_k-\rho v^2\delta_{il})u_i=0$

IXS on polycrystalline material

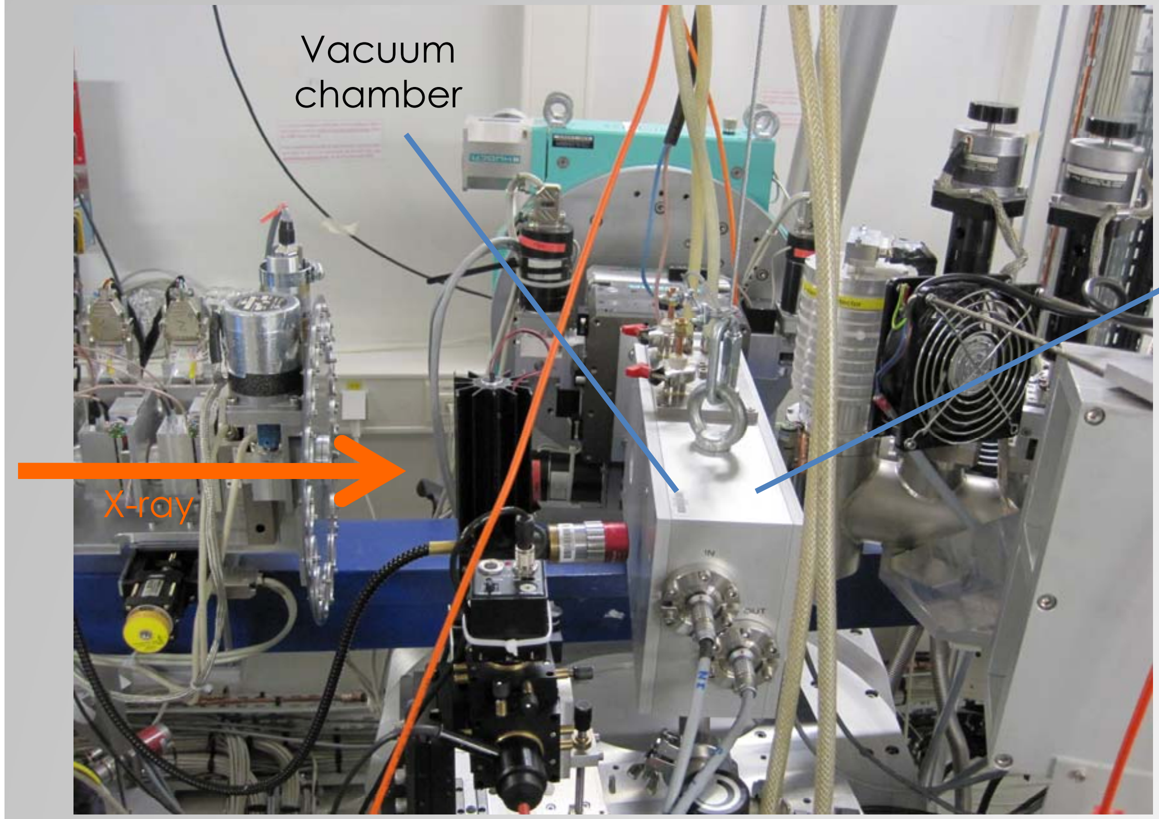
Lost of directional information → Aggregate phonon dispersion

Within the framework of the Born-Von Karman lattice dynamics theory, limited to the nearest neighbor interaction

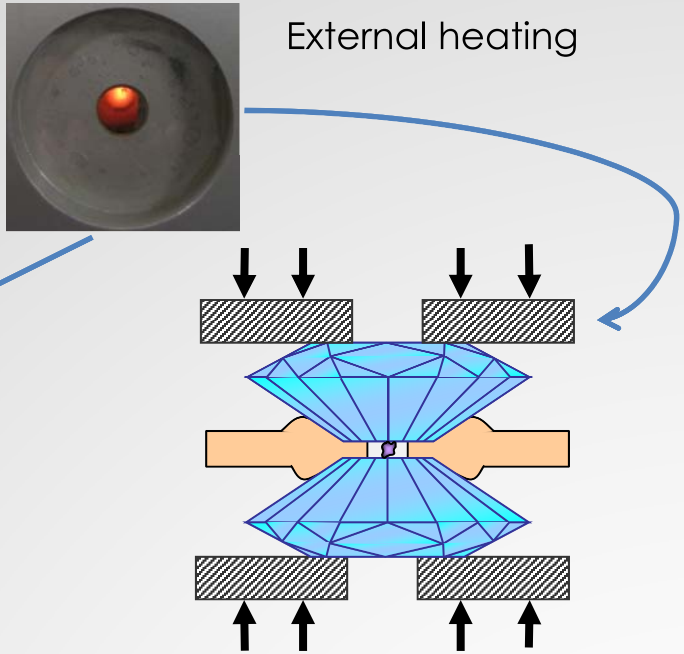
$$E = (2\hbar/\pi) V_P Q_{max} \sin[(\pi/2)(Q/Q_{max})]$$



Inelastic x-ray scattering (IXS) and x-ray diffraction (XRD) on bcc- and fcc-Fe up to 19 GPa and 1150 K



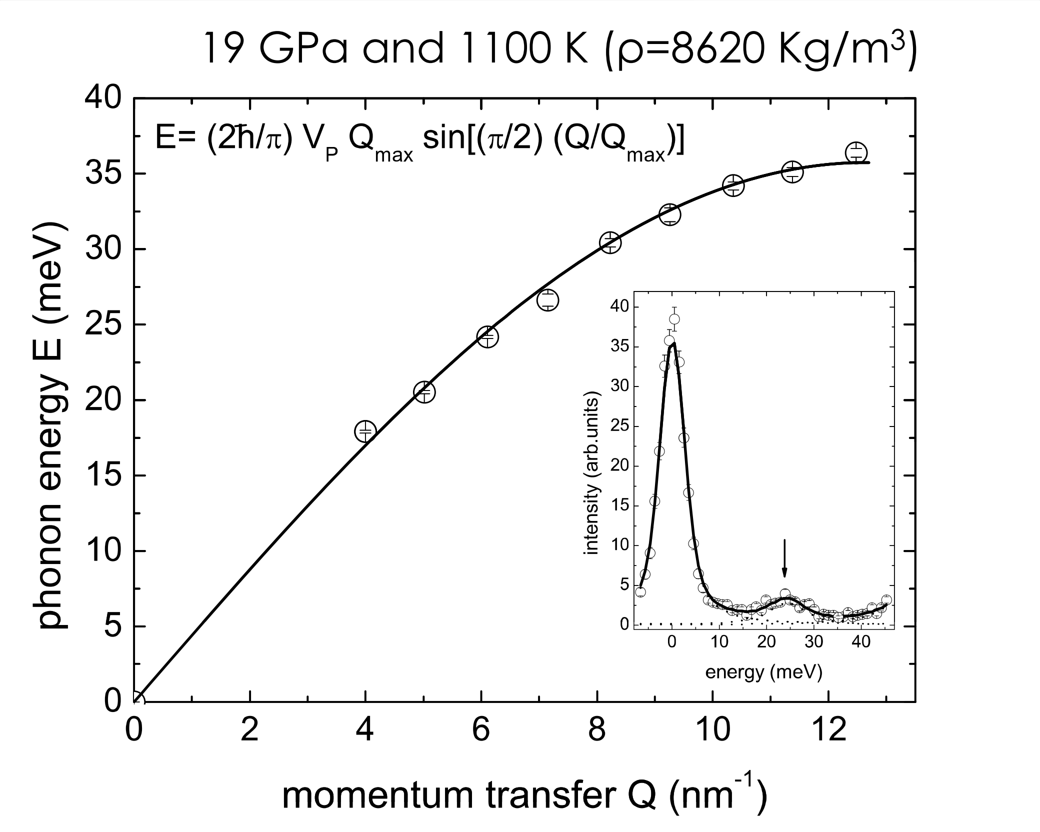
incident photon energy: 15.817 keV
energy resolution: 5.5 meV
momentum resolution: 0.25 nm^{-1}
beam size: 12x7 μm^2 (FWHM)



External heating

HP-HT by symmetric Mao DAC
Pt-wire furnace
temperature by S- thermocouple
pressure by ruby/ Fe EOS

Phonon dispersions and sound velocities

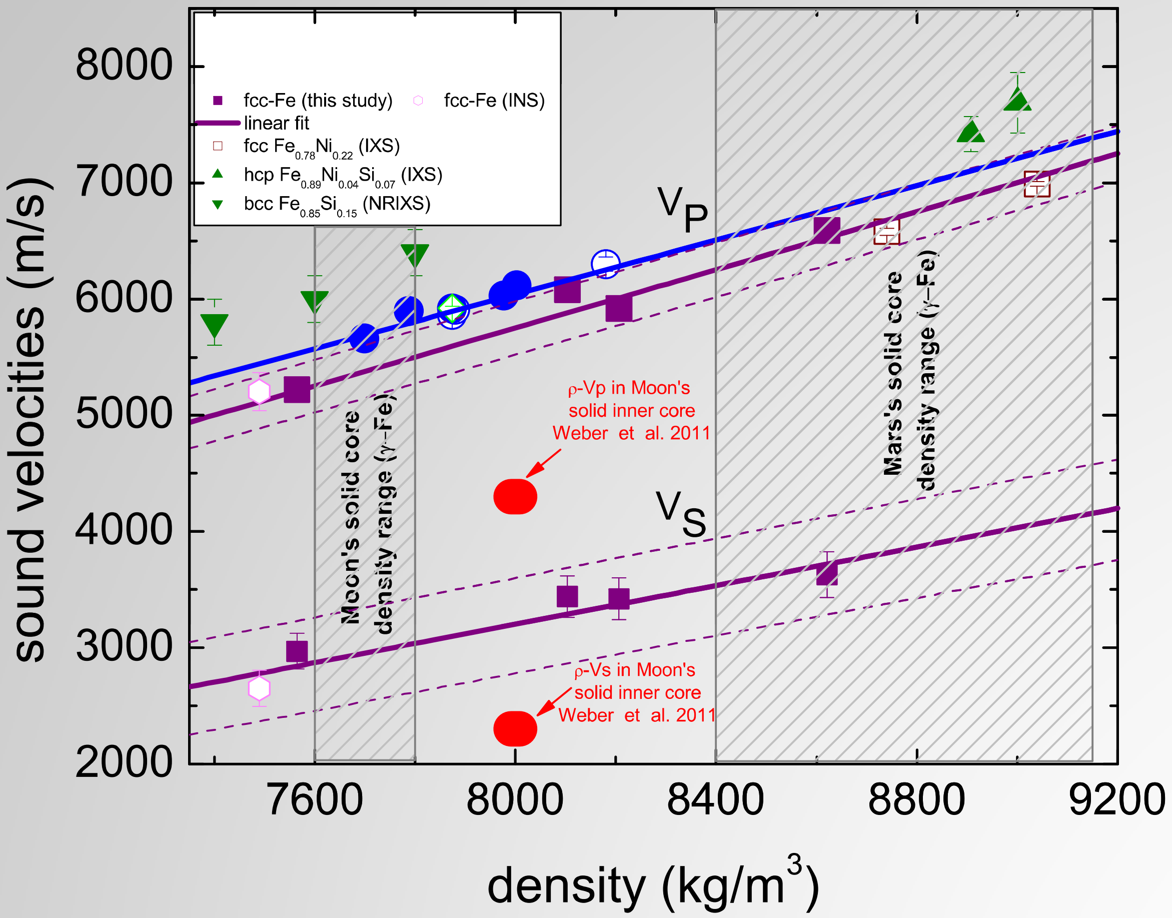


IXS → phonon dispersion → V_P

XRD → compression curve → K

IXS+XRD → $V_S=[3/4\ (V_P^2 - K/\rho)]^{1/2}$

Sound velocities vs. density



Anharmonic effects at high temperature?

~25% difference in V_P at constant density v.s.

- max 5% reduction in V_P for 400 K difference in hcp phase (Z. Mao et al., PNAS 2011)
- max 3% reduction in V_P for 400 K difference in bcc phase (Liu et al., PEPI 2014)

- 7-8% reduction in V_p at constant P for 650 K difference in pre-melting region (Martorell et al., Science 2013)

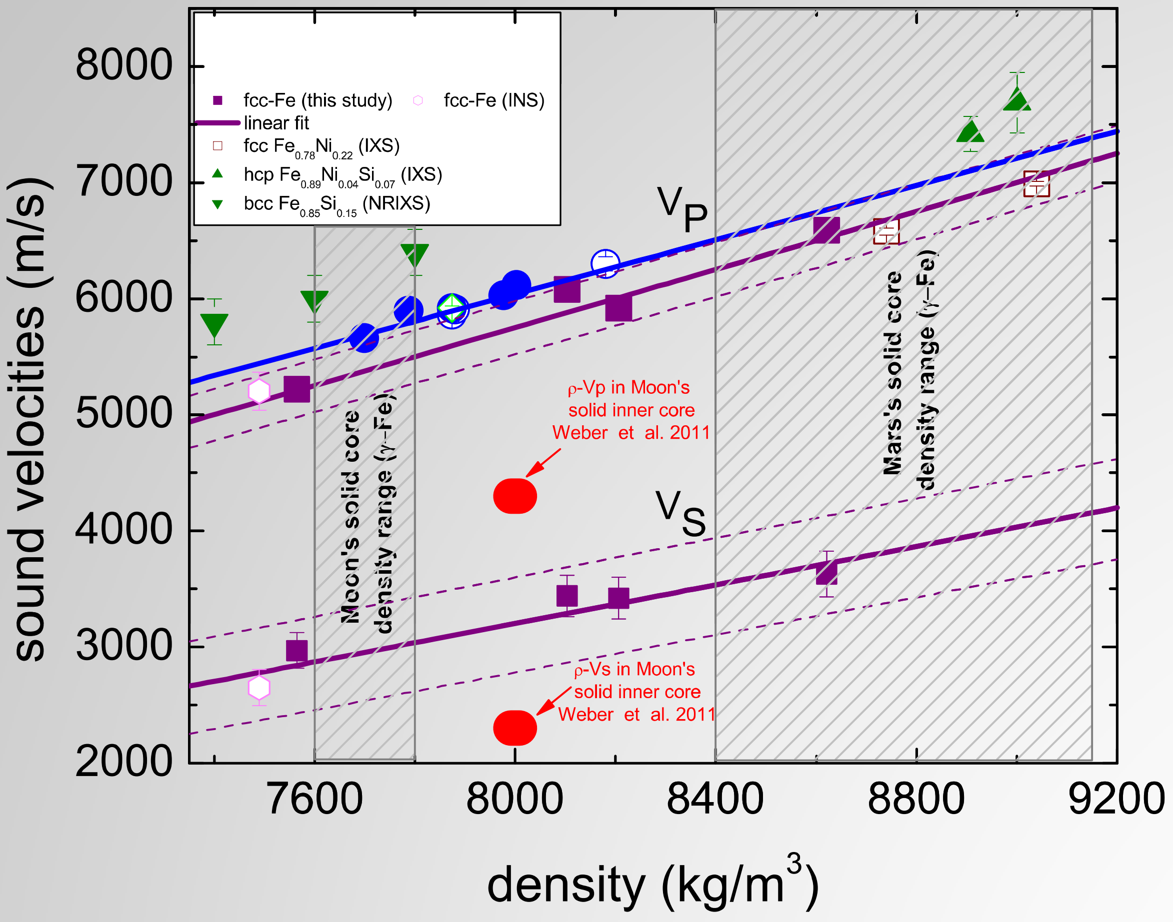
Frequency-dependent visco-elastic effects ?

~25% difference in V_P at constant density v.s.

- Moon’s core a seismic quality factor Q of ~100 (Nakamura et al., Science 1973)
- frequency dependence α~0.1-0.3 (Jackson et al., JGR 2000)

→ expected reduction ~ 1-3%

Nickel and light elements?



Ni → no effects on V_P at constant density

Light element → increase V_P at constant density

Towards a direct model of Moon's interior

The sound velocity proposed for the Moon's inner core is incompatible with that of pure solid iron or any plausible solid iron alloy

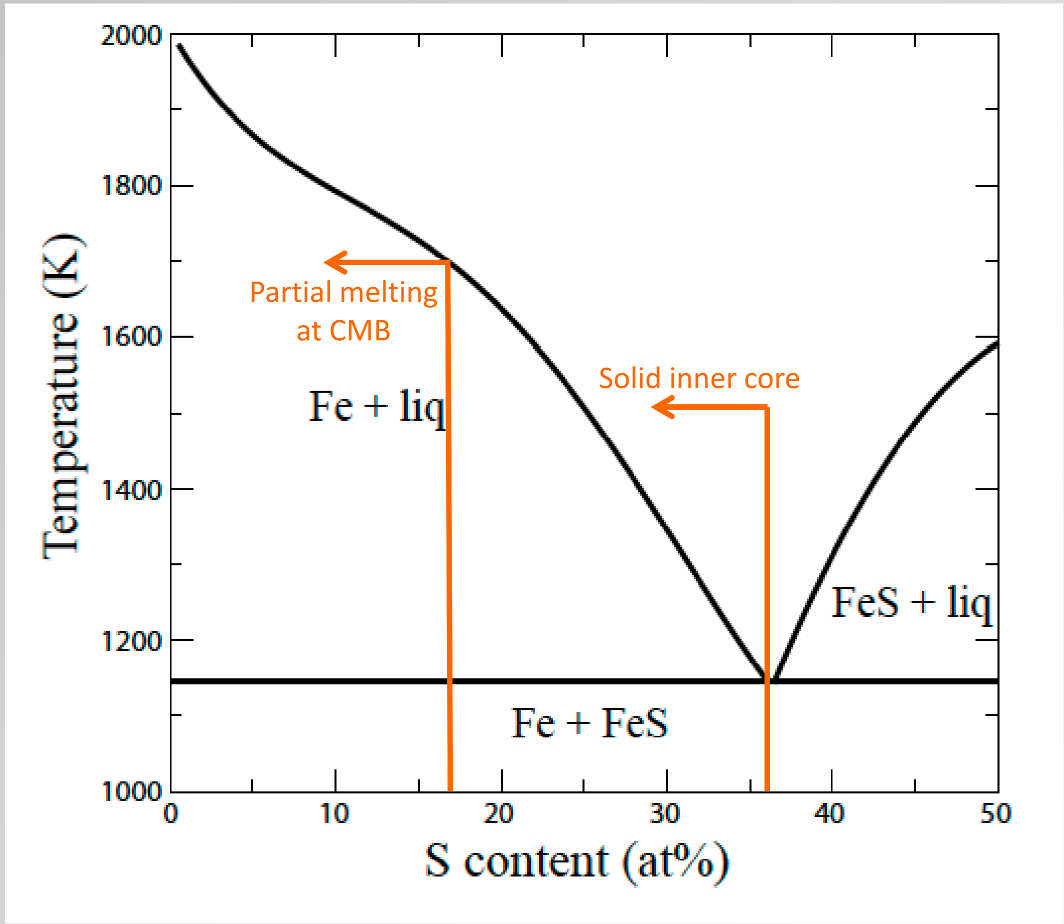
after Weber et al., Science 2011

lunar seismic data, lunar moment of inertia

1) seismic reflector exists at ICB
2) liquid outer core

Reanalysis of seismic results on the basis of mineral physics constraints

Fe-FeS phase diagram at 5 GPa

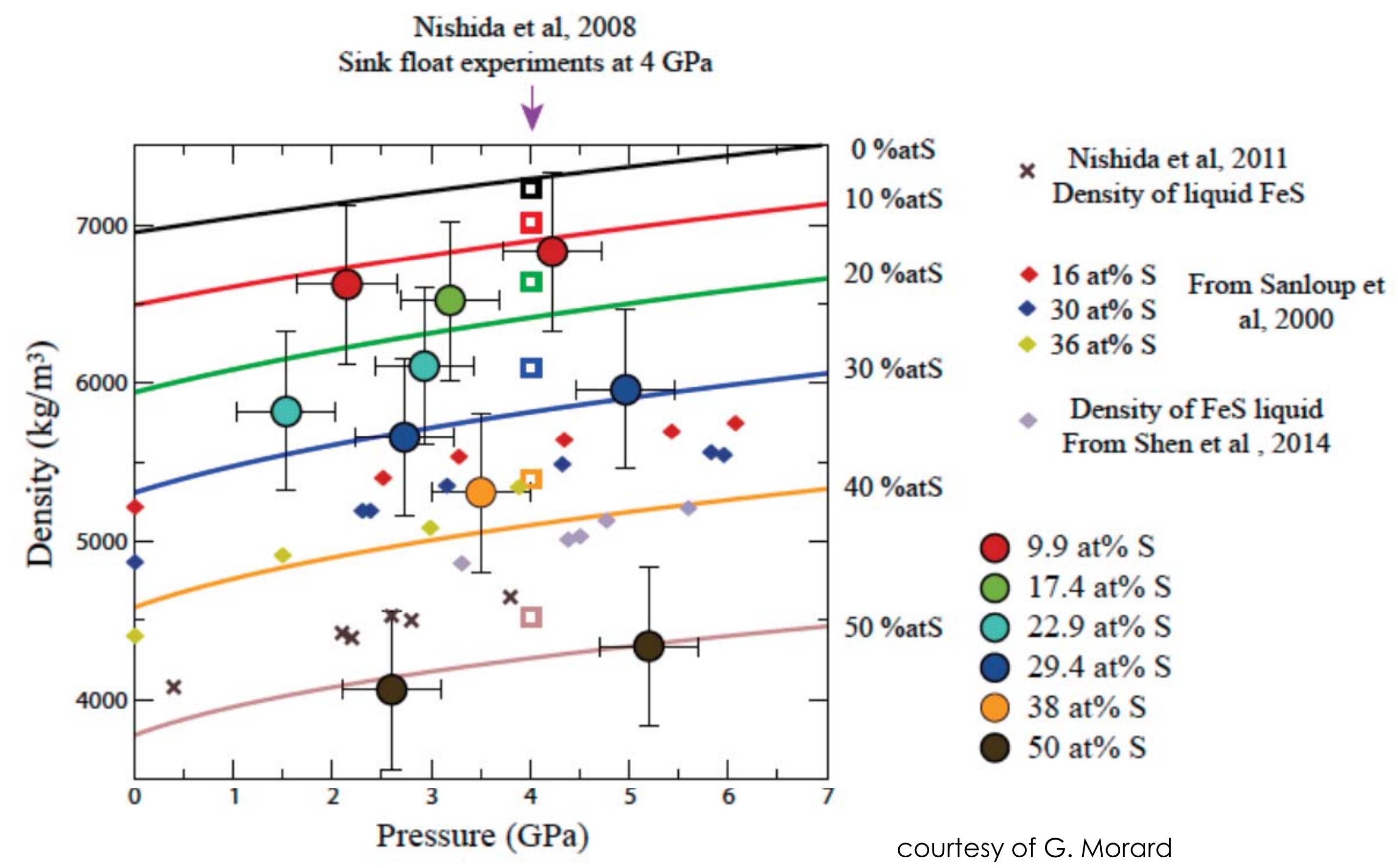


after Buono & Walker, CGA 2011

- Solid inner core: pure γ-Fe
- Liquid outer core: Fe-S (10-20 at% S)
- ICB at ~5 GPa and ~1700-1900 K

Density and sound velocities in the outer core

Liquid Fe-S alloys at 1900 K

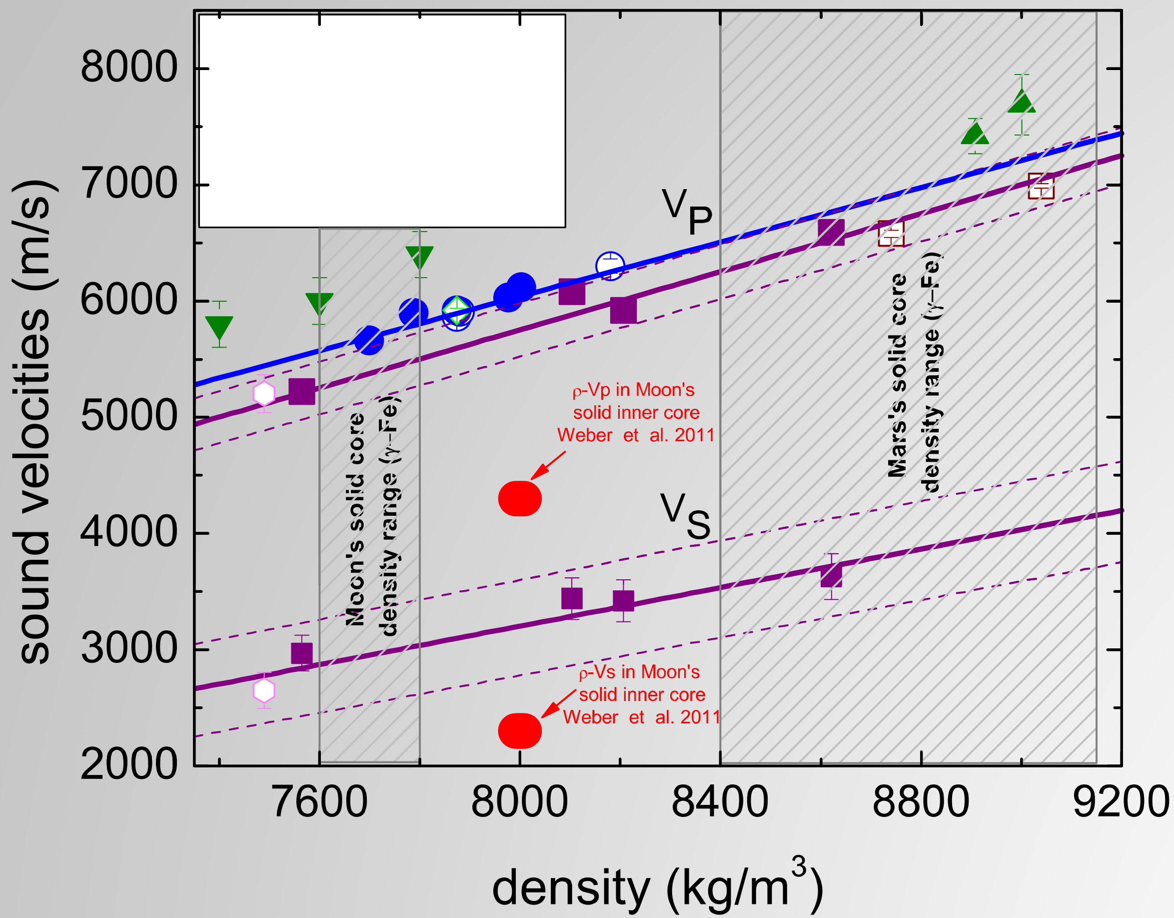


courtesy of G. Morard

ρ: 6500-7000 kg/m^3
V_P: 3600-4000 m/s

Density and sound velocities in the inner core

Solid γ-Fe at 1100 K

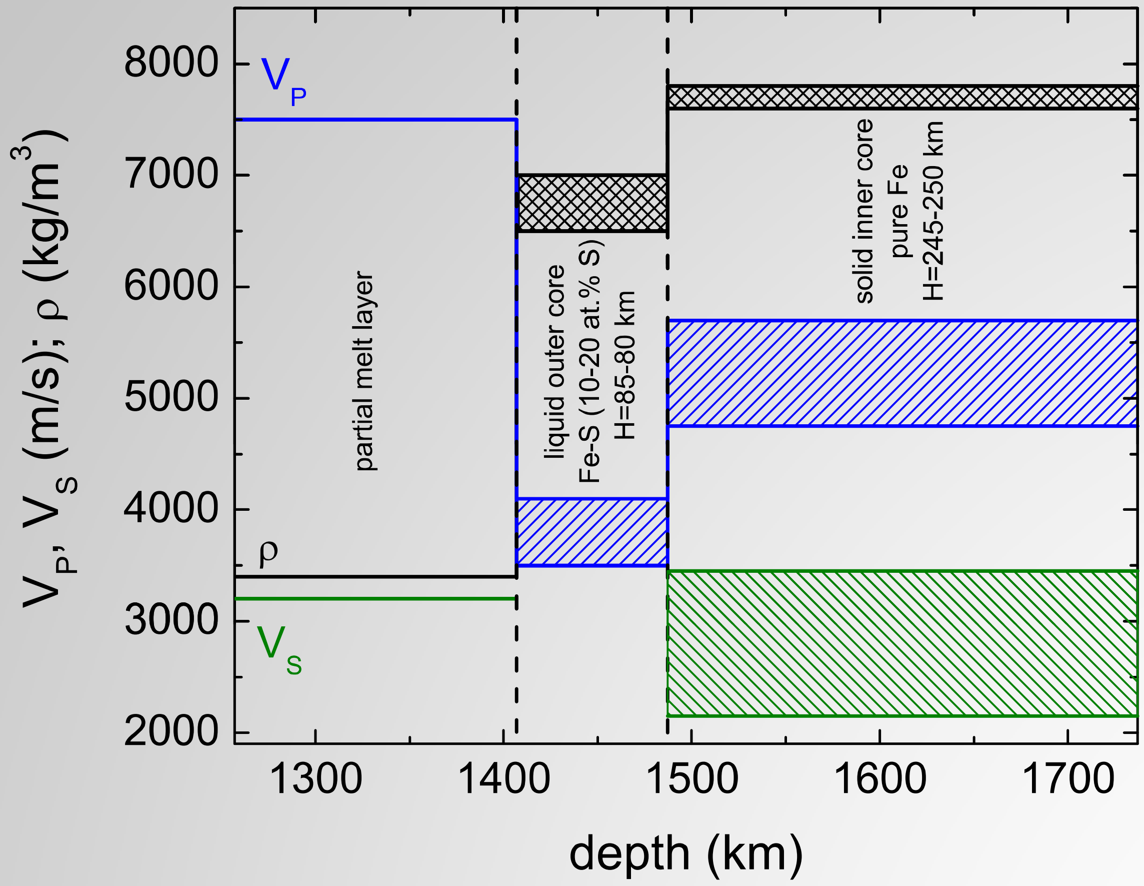


Possible effects at higher T
T from 1100 K to 1900 K

- up to 5% reduction in V_P
- up to 10% reduction in V_S

ρ: 7600-7800 kg/m^3
V_P: 4750-5700 m/s
V_S: 2150-3400 m/s

A mineral physics reference model for the Moon's core



matching within 0.1% known values of lunar mass and moment of inertia

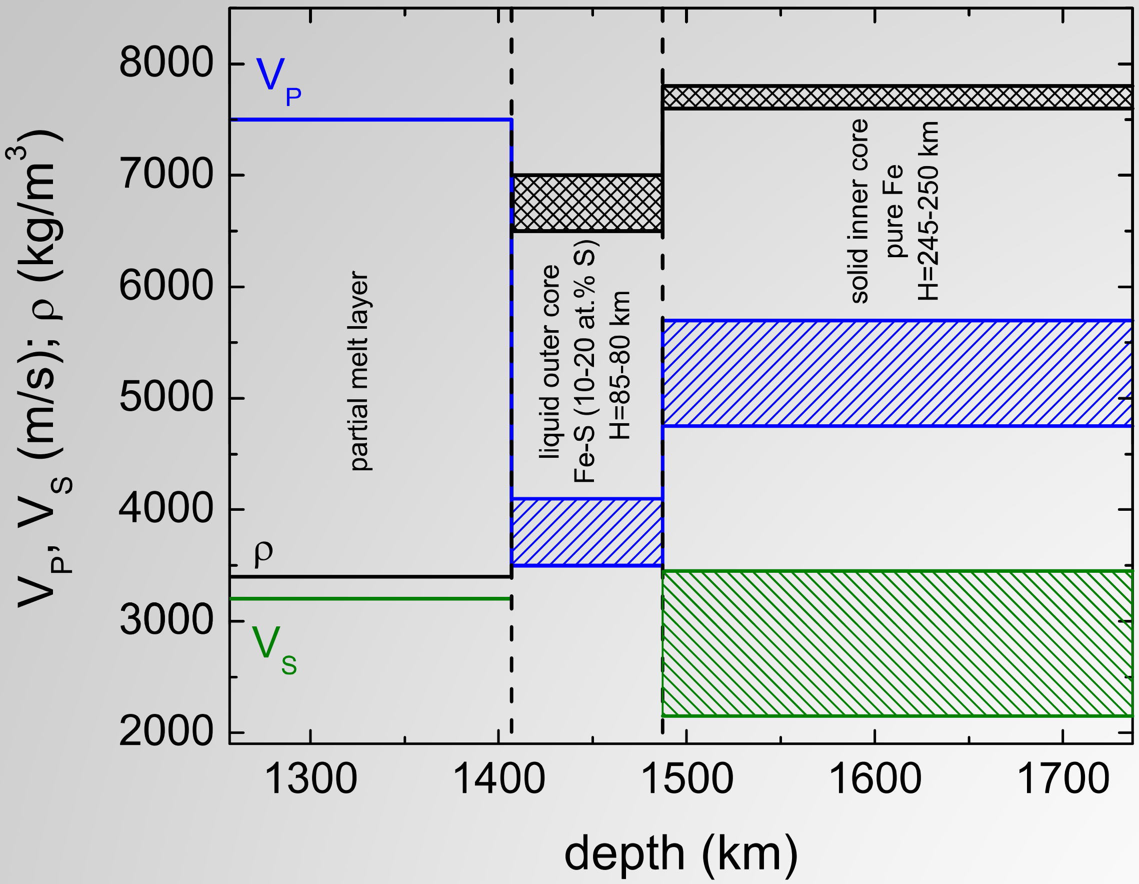
Sulphur content

mass balance → 3-6 wt.% S in the Moon's core

lunar core formation and metal/silicate partitioning of siderophile elements (Rai & van Westrenen, EPSL, 2014))
→ up to 6 wt.% S

(long-lived, now extinct) lunar dynamo modeling (Laneuville et al., EPSL 2014)
→ 6 to 8 wt.% S

A mineral physics reference model for the Moon’s core



Outlooks

- Sound velocity measurements in solids at higher T

- Sound velocity measurements in liquid samples

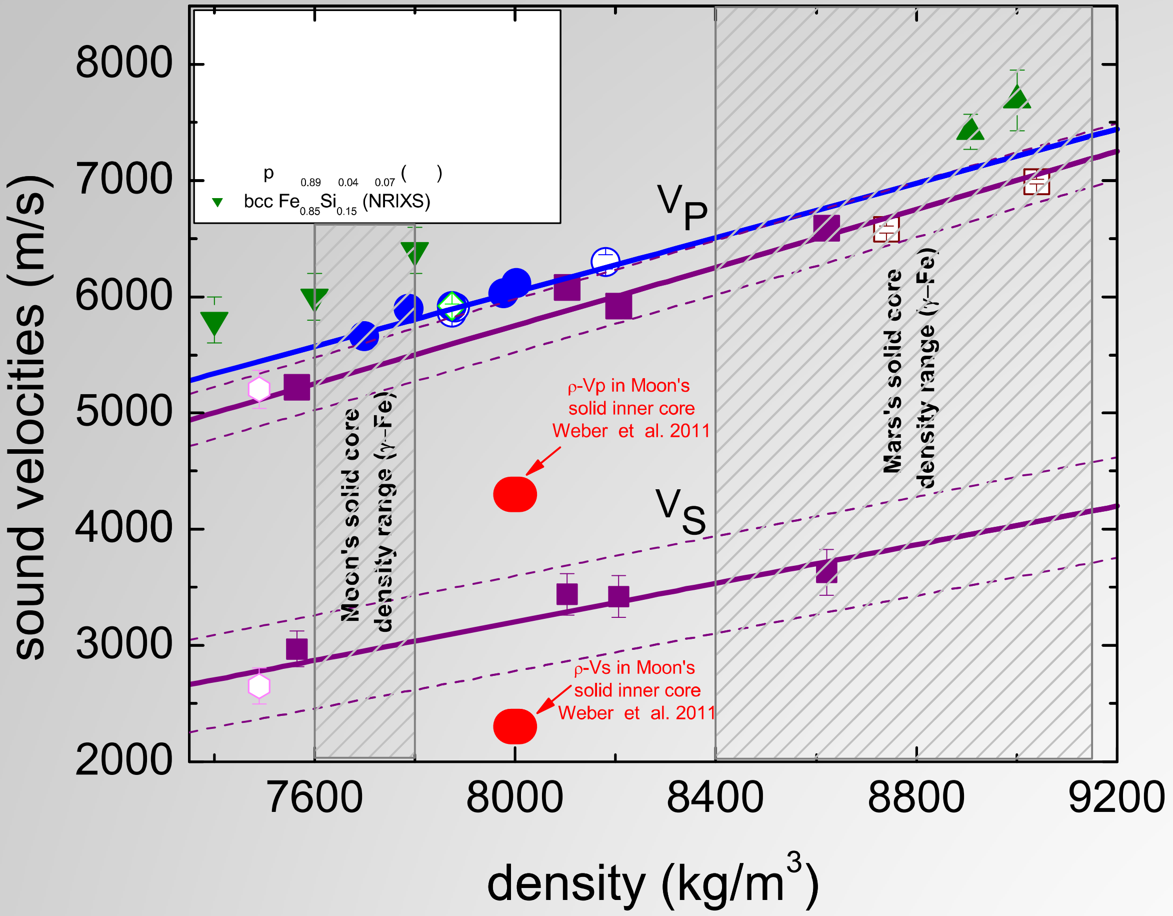
    - Nishida et al., EPSL 2013, measurements on Fe-S(30 wt.%)
    - Jing et al., EPSL 2014, measurements on Fe-S (10, 20 and 27wt%)

- Refinement of core radius from tidal dissipation and Love numbers

- Independent constraints on core temperatures?

- …

Extrapolation to telluric planetary cores up to Mars size



Mars core: γ-Fe at 42 GPa and 2500 K (ρ~9100 Kg/m^3)

→ V_P ~7100 m/s; V_S ~3600-4400 m/s

InSight NASA Discovery mission (launch in March 2016)

Acknowledgment

Guillaume Morard, Guillaume Fiquet

UNIVERSITY OF MARYLAND

Nicholas C. Schmerr

THE UNIVERSITY OF EDINBURGH

Tetsuya Komabayashi

ESRF
The European Synchrotron

Michael Krisch

Yingwei Fei

GEOPHYSICAL LABORATORY
Carnegie Institution of Washington

Agence Nationale de la Recherche
ANR

grant no. 2010-JCJC-604-01
grant no. ANR-12-BS04-0015-04

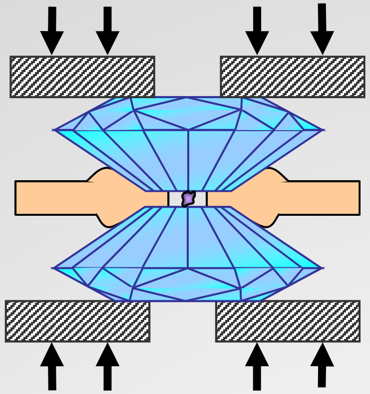
NASA

grant no. NNX11AC68G
grant no. NNX09AO80G

IXS particularly well suited for extreme conditions

Sample volume < 10^{-5} mm^3

Beam size < 100 μm



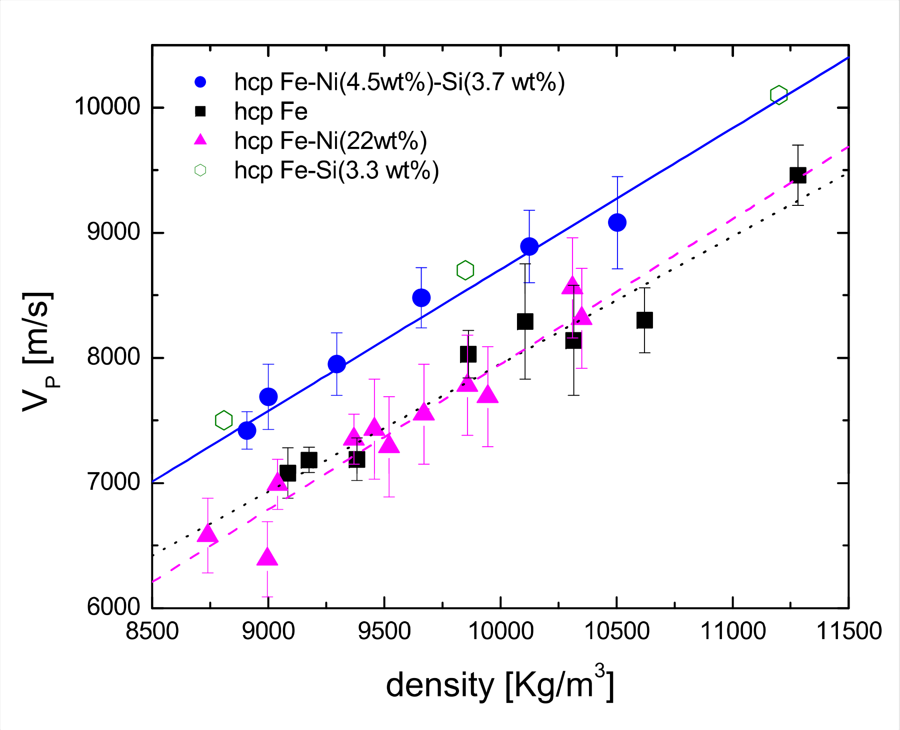
Large variety of samples

Metals as well as semiconductors or insulators

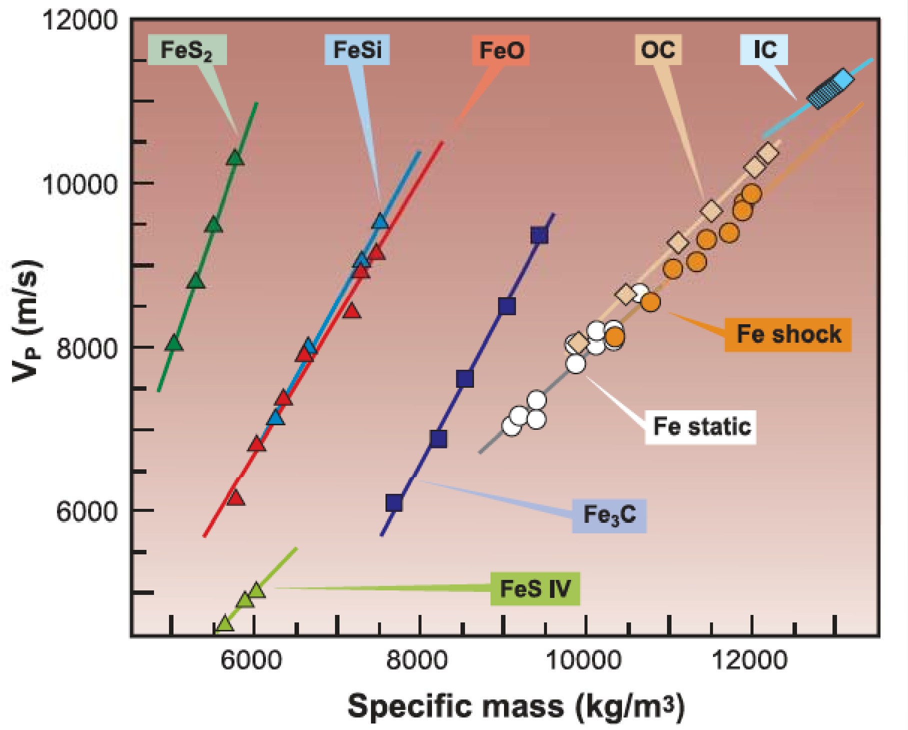
Opaque as well as transparent materials

Single crystals, powders, liquid, glasses

Nickel and light elements?



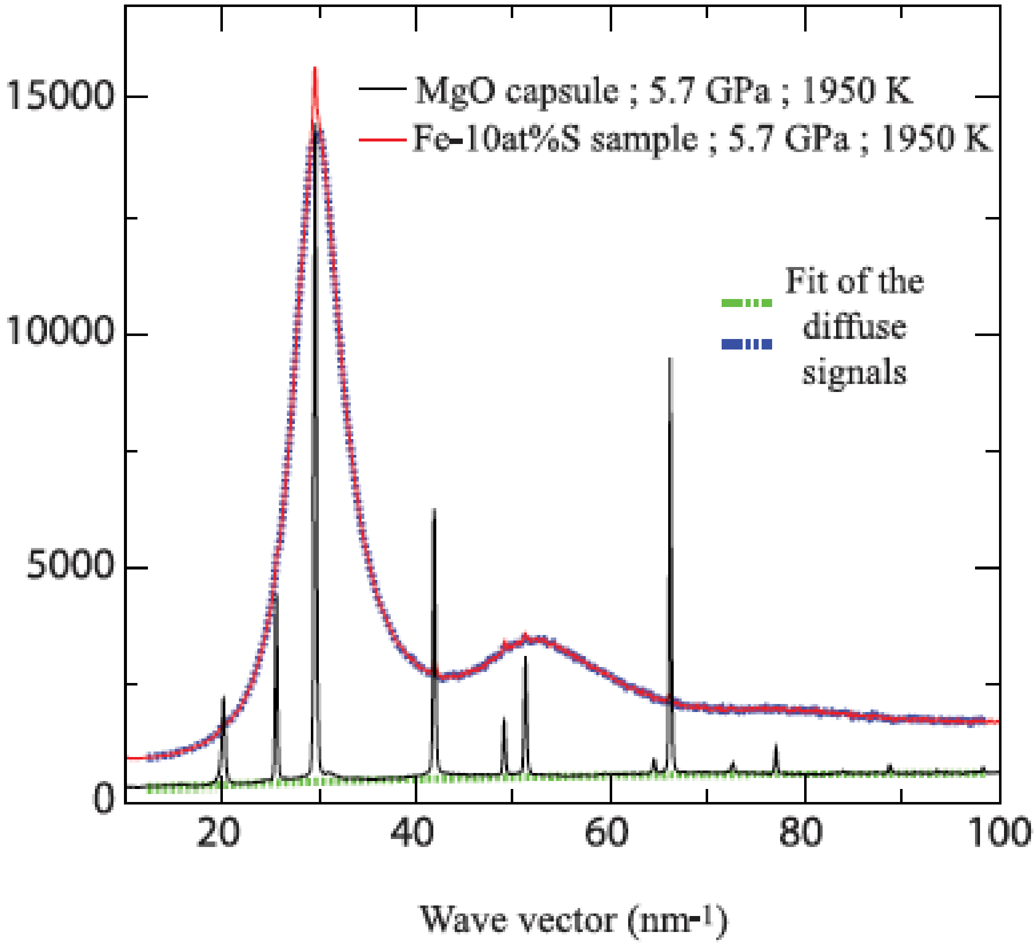
Antonangeli et al., EPSL 2010
Kantor et al., PEPI 2007
Tsuchiya and Fujibuchi, PEPI 2009



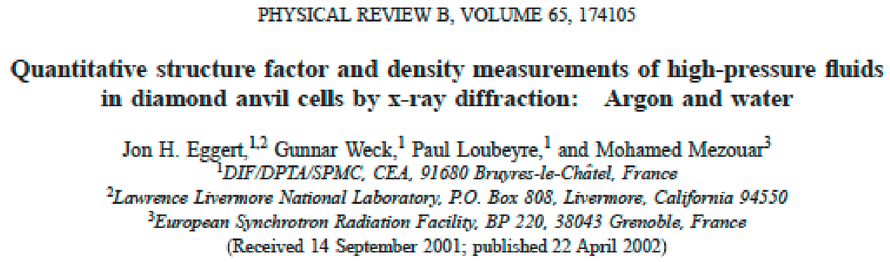
Badro et al., EPSL 2007;
Fiquet et al., PEPI 2009

Ni → no effects on V_P at constant density
Light element → increase V_P at constant density

Paris Edinburgh Press



Density of liquids from g(r)



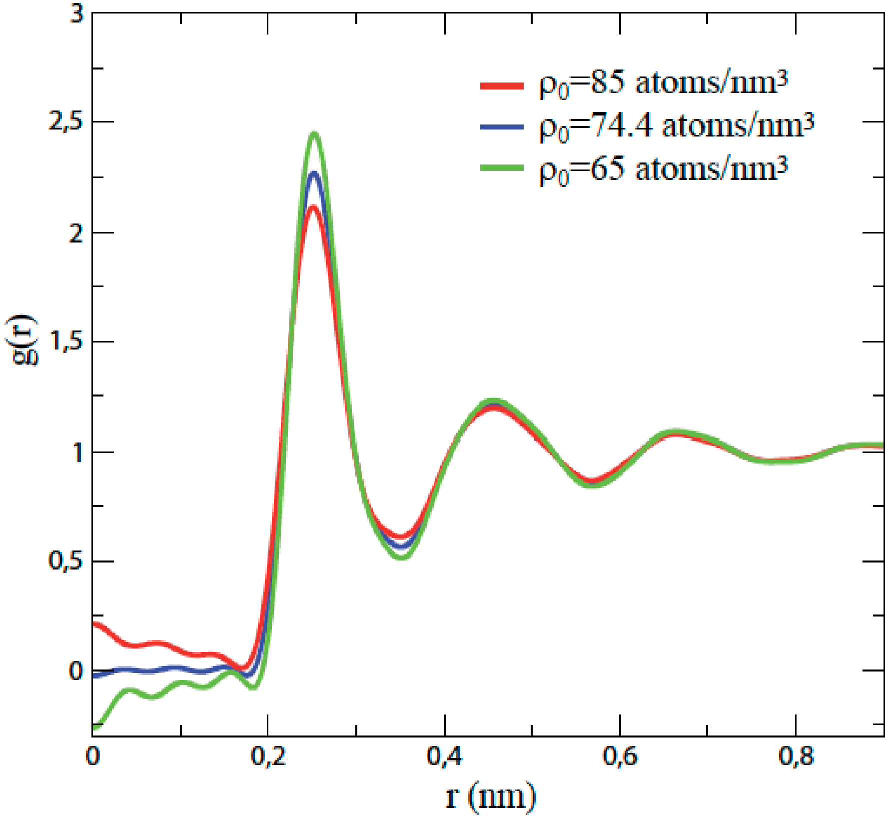
PHYSICAL REVIEW B, VOLUME 65, 174105

Quantitative structure factor and density measurements of high-pressure fluids in diamond anvil cells by x-ray diffraction: Argon and water

Jon H. Eggert,[1,2] Gunnar Weck,[1] Paul Loubeyre,[1] and Mohamed Mezouar[3]
[1]*DIF/DPTA/SPMC, CEA, 91680 Bruyres-le-Châtel, France*
[2]*Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550*
[3]*European Synchrotron Radiation Facility, BP 220, 38043 Grenoble, France*
(Received 14 September 2001; published 22 April 2002)

$$\chi^2_{(n)}(\rho_0,s) \equiv \int_0^{r_{min}} [\Delta F_{(n)}(r)]^2 dr.$$

By adjusting the density ρ_0 and the scaling factor for the background signal s, a unique solution can be found.



Density and sound velocity for Fe-S liquid alloy

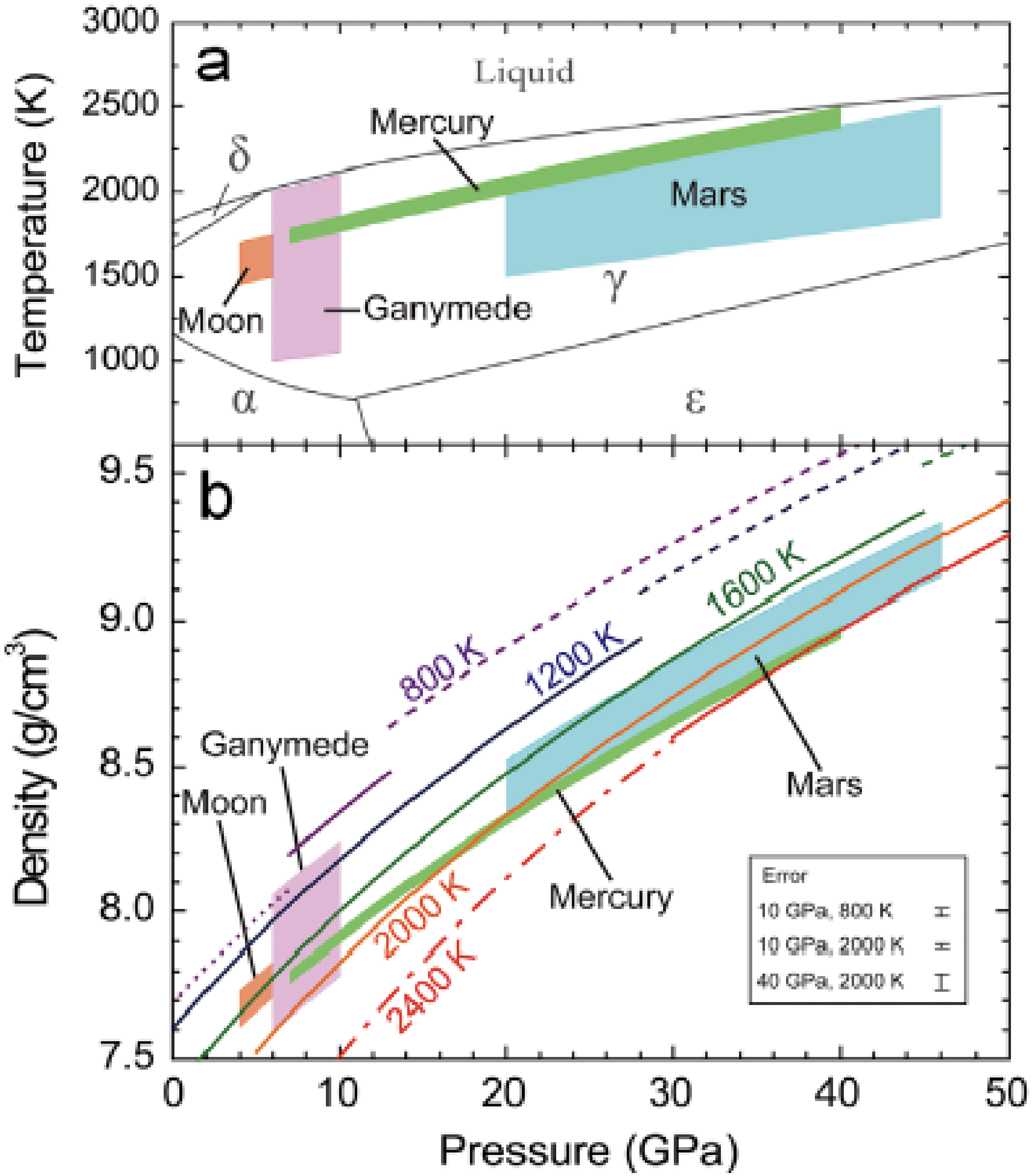
Modelling:
3rd order Birch Murnaghan equation of state EOS(K_{T0}, K')

Approximations:
αK_T and $\gamma\rho$ constant as a function of pressure
($\gamma = \alpha K_T / \rho C_V$)

$$V_P = [(1+\alpha\gamma T)\ K_T\ /\ \rho]^{1/2}$$

Assumptions:
constant C_V with S content
linear dependence the evolution of $\delta\rho/\delta T$ with S content

P (GPa)	T (K)	ρ (Kg/m^3)	phase	V_P (m/s)	V_S (m/s)
0	300	7875	bcc	5920±40	
2.5	800	7790	bcc	5900±40	
3.1	300	7975	bcc	6030±70	
3.3	1020	7700	bcc	5660±70	
7.3	800	8000	bcc	6120±70	
0	1150	7560	fcc	5220±70	2970±150
7	1000	8105	fcc	6080±70	3440±180
10	1100	8205	fcc	5920±60	3420±180
19	1100	8620	fcc	6590±70	3630±200


a
Temperature (K)
3000
2500
2000
1500
1000
Liquid
Mercury
δ
Mars
γ
Moon
Ganymede
α
ε
b
Density (g/cm^3)
9.5
9.0
8.5
8.0
7.5
800 K
1200 K
1600 K
2000 K
2400 K
Ganymede
Moon
Mars
Mercury
Error
10 GPa, 800 K
10 GPa, 2000 K
40 GPa, 2000 K
0
10
20
30
40
50
Pressure (GPa)