Some open questions in the study of WDM/HEDM using laser driven shock

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Acknowledgment

Peter Celliers, UBC
Luiz Da Silva, UBC
Andrew Forsman, UBC
Dean Parfeniuk, UBC
Jim Waterman, UBC
Guang Xu, UBC

Neil Ashcroft, Cornell
M. Basko, ITEP
Budi Godwal, BARC
Raymond Jeanloz, UCB
A. Kendl, MPQ
V.N. Kondrashov, Troitsk Inst.
Thorsten Lower, MPQ
Jurgen Meyer-ter-Vehn, MPQ
Richard Sigel, MPQ

*Research supported by NSERC, Canada

Laser driven shock wave is widely used in the study of WDM/HEDM

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- **In a steady strong shock, a homogeneous state of WDM/HEDM is formed behind the shock front**
- **As a Hugoniot state, it can be characterized by shock speed that is easily measured**
- **Laser-driven shock provides ready access to Mbar regime & picosecond optical diagnostics**

This talk focuses on some open questions raised by our earlier studies on

- Electron-ion coupling

- Phase transition kinetics

One of these studies started as an EOS experiment

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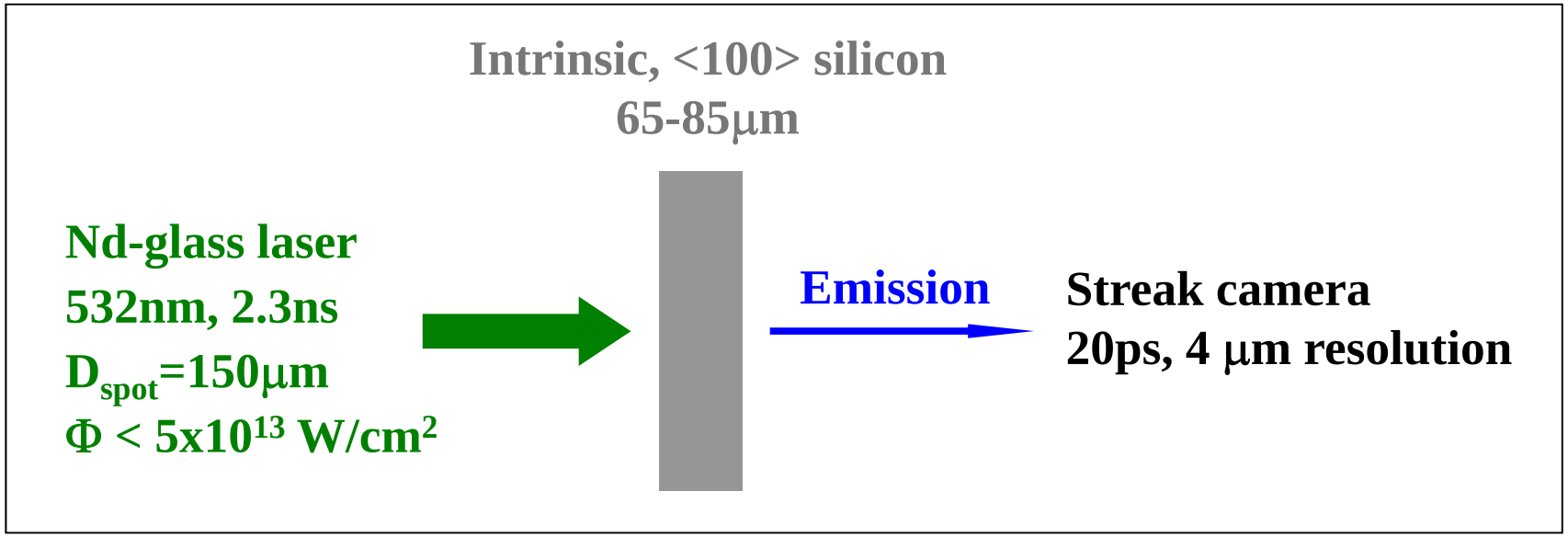
- **The experiment is to measure brightness temperature of shocked silicon**

- **With an indirect band gap of 1.2eV, absorption coefficient of silicon is $<10^4$ cm^{-1} for $\lambda>0.5\mu m$, allowing observation of optical emission from shock wave in flight before it reaches the free surface**



The EOS experiment turned into a study of *e-i* equilibration in a shock wave

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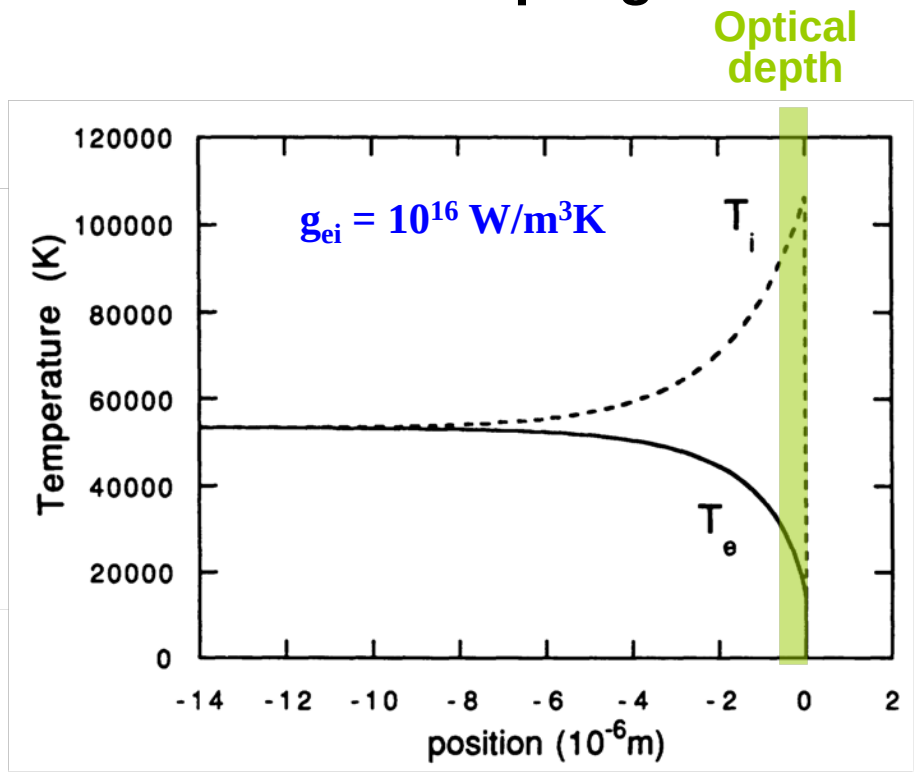
- **Absolute intensity of emission from shock wave in-flight was an order of magnitude below that predicted for an equilibrium (T_e=T_i) shock front**

- **2-T model showed existence of T_e and T_i gradients at shock front governed by the electron-ion coupling constant (g_{ei} or g)**

$$C_e \frac{\partial T_e(x,t)}{\partial t} = g[T_i(x,t) - T_e(x,t)] + \frac{\partial}{\partial x}\kappa(n_e,T_e)\frac{\partial}{\partial x}T_e(x,t)\,,$$

$$C_i \frac{\partial T_i(x,t)}{\partial t} = g[T_e(x,t) - T_i(x,t)]\,,$$



Shock front became a means to probe g_{ei}

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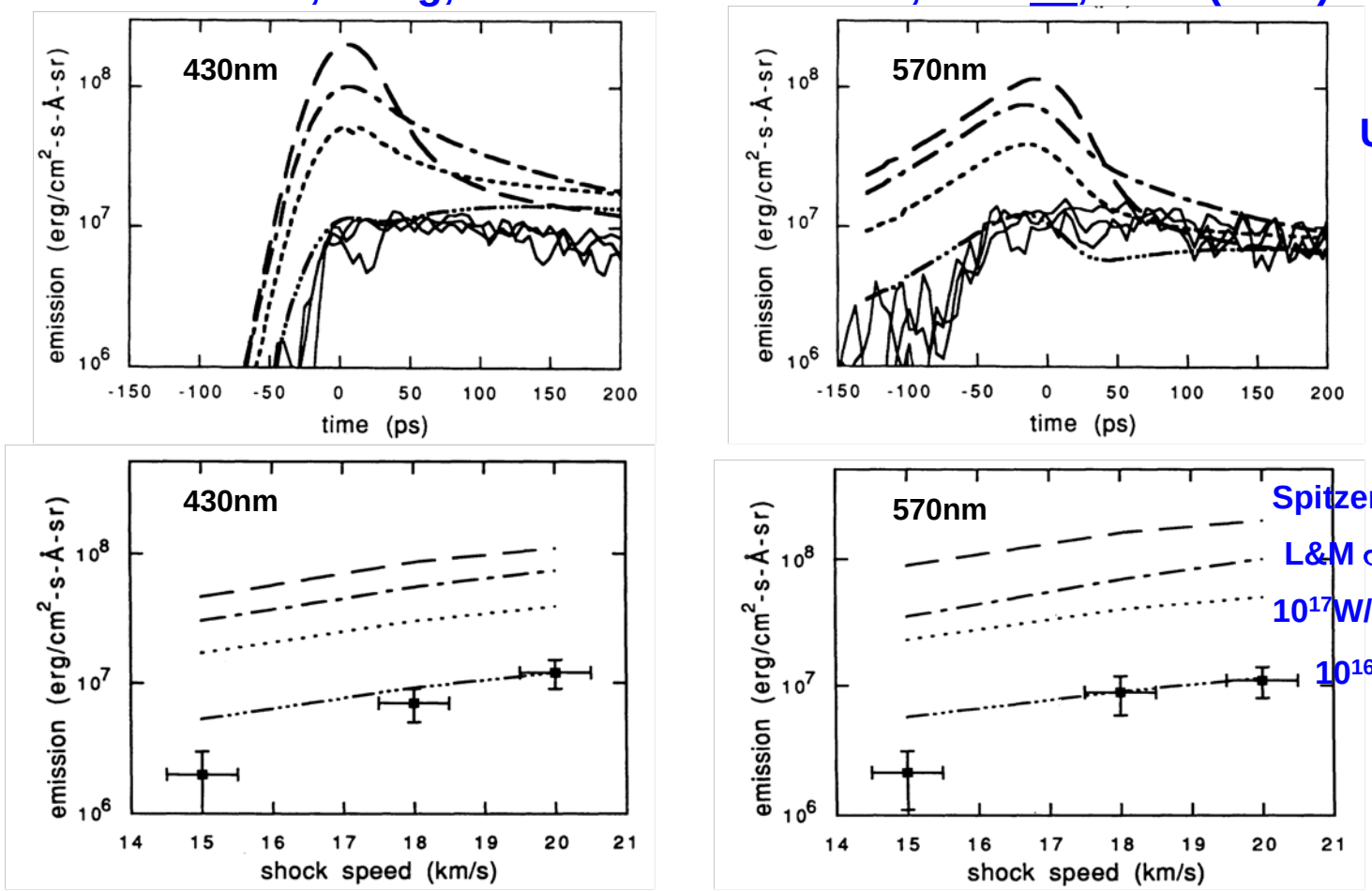
- Emission risetime consistent with opacity of cold silicon
- Inferred g_{ei} much lower than Landau-Spitzer results

P. Celliers, A. Ng, G. Xu and A. Forsman, PRL 68, 2305 (1992)



$U_s = 2\times10^6$ cm/s

Analysis based on calculated emissivity

Model-dependent emissivity was removed in an improved experiment at MPQ

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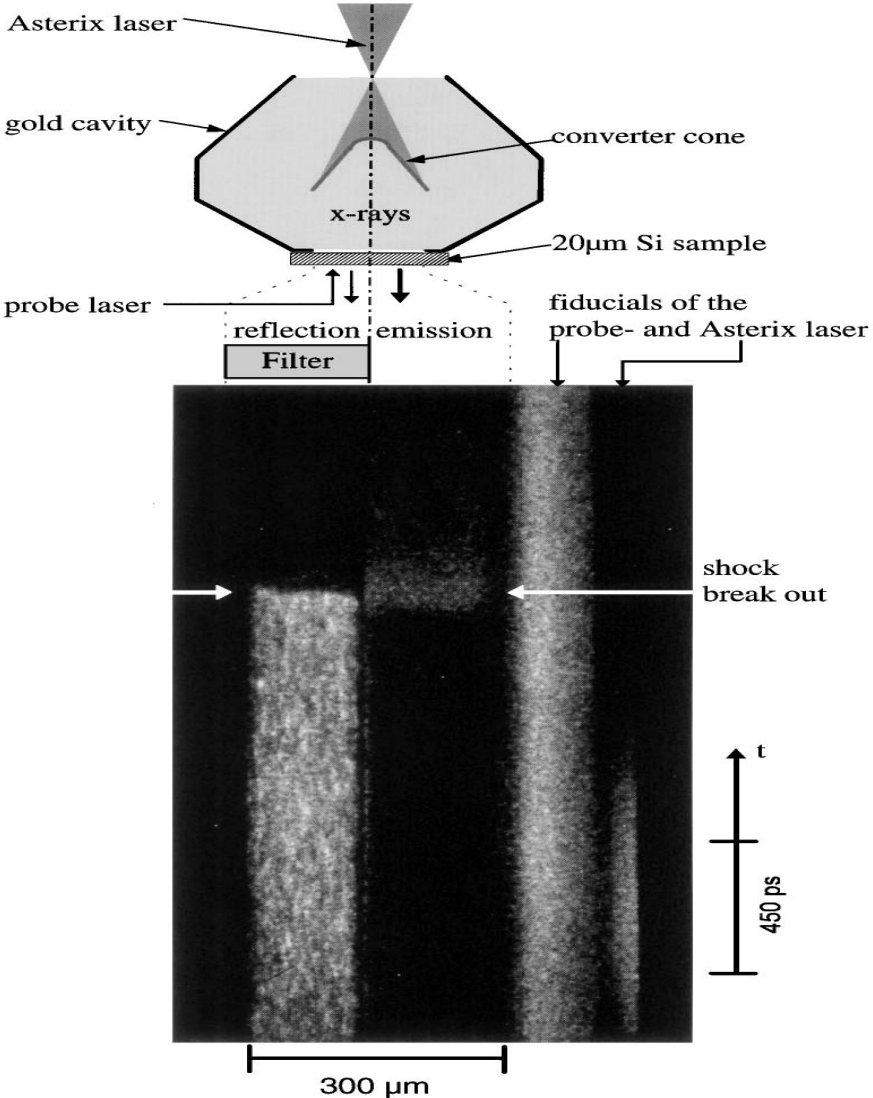
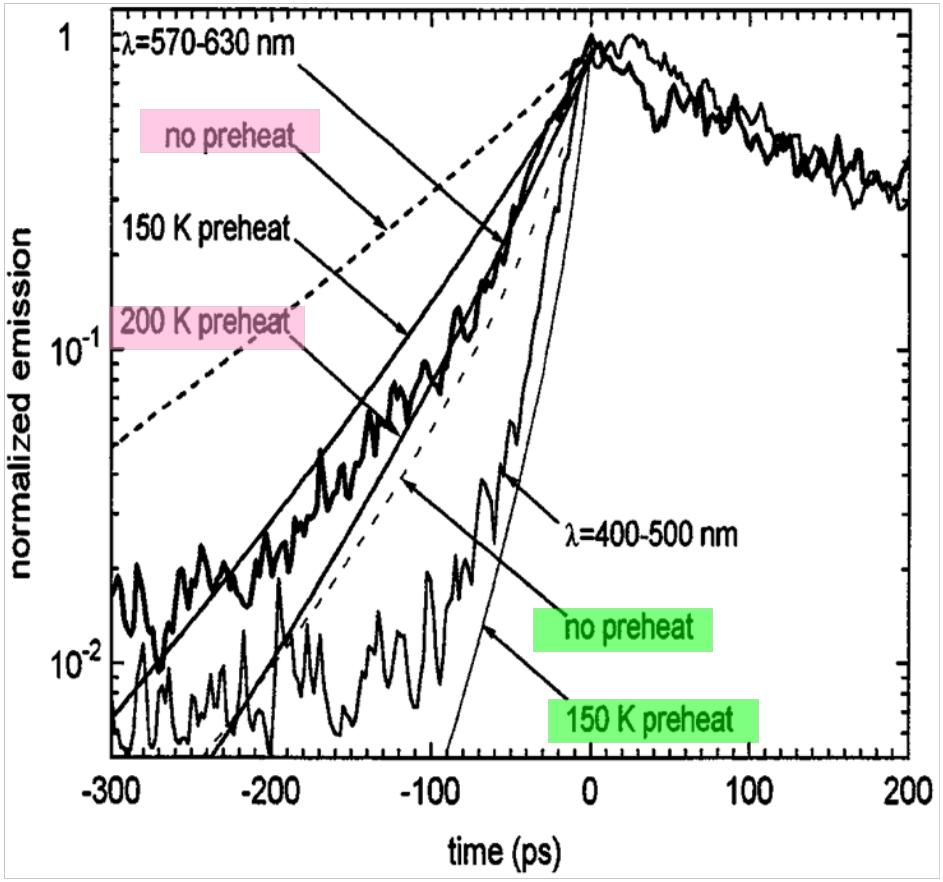
- X-ray drive to improve uniformity & planarity of shock front
- Simultaneous measurements of shock front emission & reflectivity



Radiative preheat <200K



MPQ experiment corroborated UBC findings

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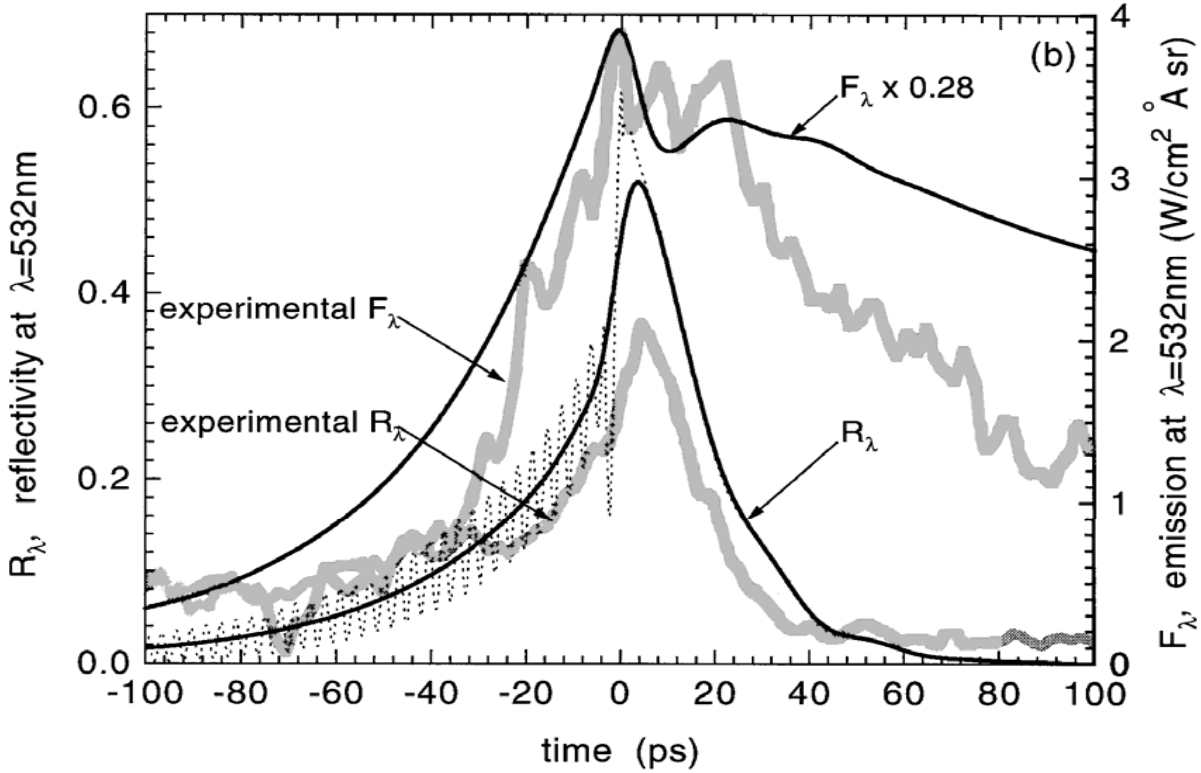
- **For a 6.6 Mbar (20.7 km/s) shock in silicon, T_{br}=1.4±0.1 eV of shock front is much lower than the Hugoniot value of 4.3 eV**

- **Absolute intensity consistent with model for $g_{ei}=10^{16}$ W/m^{3}K**

Th. Lower, V.N. Kondrashov, M. Basko, A. Kendl, J. Meyer-ter-Vehn, R. Sigel and A. Ng, PRL 80, 4000 (1998)



Lower g_{ei} also noted in other work

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- **A similar experiment of shocked aluminum**
  - **M. Basko, Th. Lower, V.N. Kondrashov, A. Kendl, R. Sigel, and J. Meyer-ter-Vehn, PRE 56, 1019 (1997)**
  - **Interpretation was complicated by release of the free surface when shock wave emerges**

- **Energy relaxation rates calculations for dense Al, C and Si plasmas with $T_e > T_i$**
  - **M.W.C. Dharma-wardana, PRE 64, 035401 (2001)**
  - **Strong coupling theory (coupled-mode approach) predicted an order of magnitude reduction in energy relaxation rates**

Key questions remain and there are much more to explore

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- **How can we verify nonequilibrium conditions at shock front?**
  - **Measurement of electron temperature far behind the shock front**
  - **Measurement ion temperature at shock front**

- **What other measurements of g_{ei} can be made in similar regimes?**
  - **Assessing g_{ei} from reflectivity and emission intensity as a shock wave evolves across an interface**
    - **A. Ng and T. Ao, PRL 91, 035002 (2003)**
  - **Determining g_{ei} from observation of thermal conduction waves driven by intense femtosecond laser ($T_e > T_i$)**
    - **A. Ng, A. Forsman and G. Chiu, PRL 81, 2914 (1998)**

Another study was observation of shock formation & propagation in quartz

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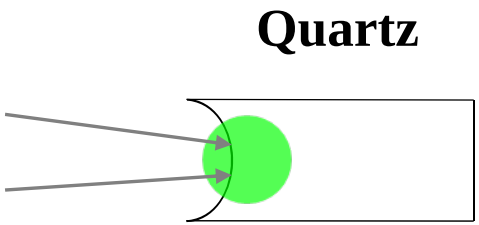
- **Shock formation & propagation in quartz were probed with shadowgraphy and Schlieren measurements**

532nm, 2ns
Nd-glass laser

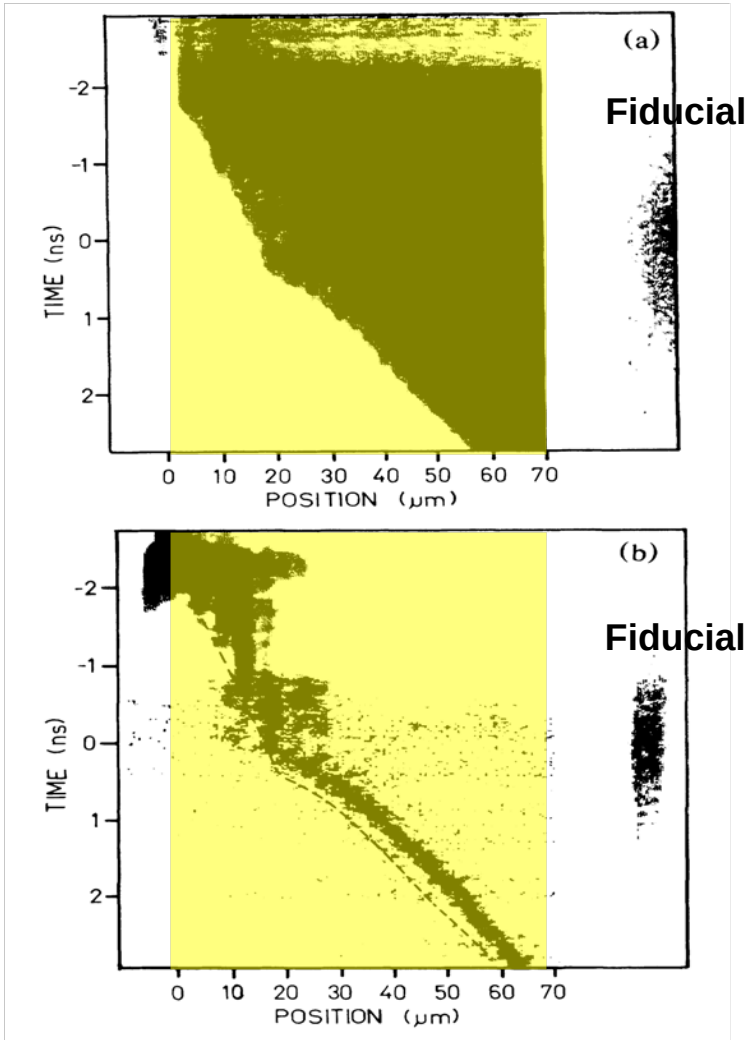
D_{60}=40μm

D_{90}=80μm

$\Phi_{60}<10^{14}$W/cm^2



570nm, 2ns dye laser illuminating target onto streak camera



Shock trajectory showed anomalous behavior

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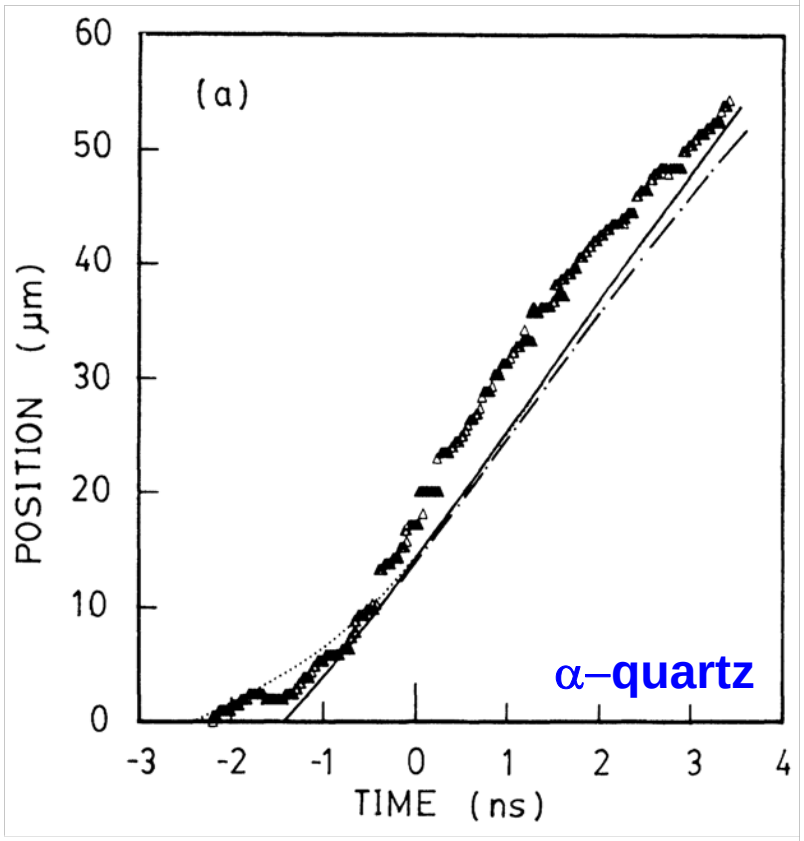
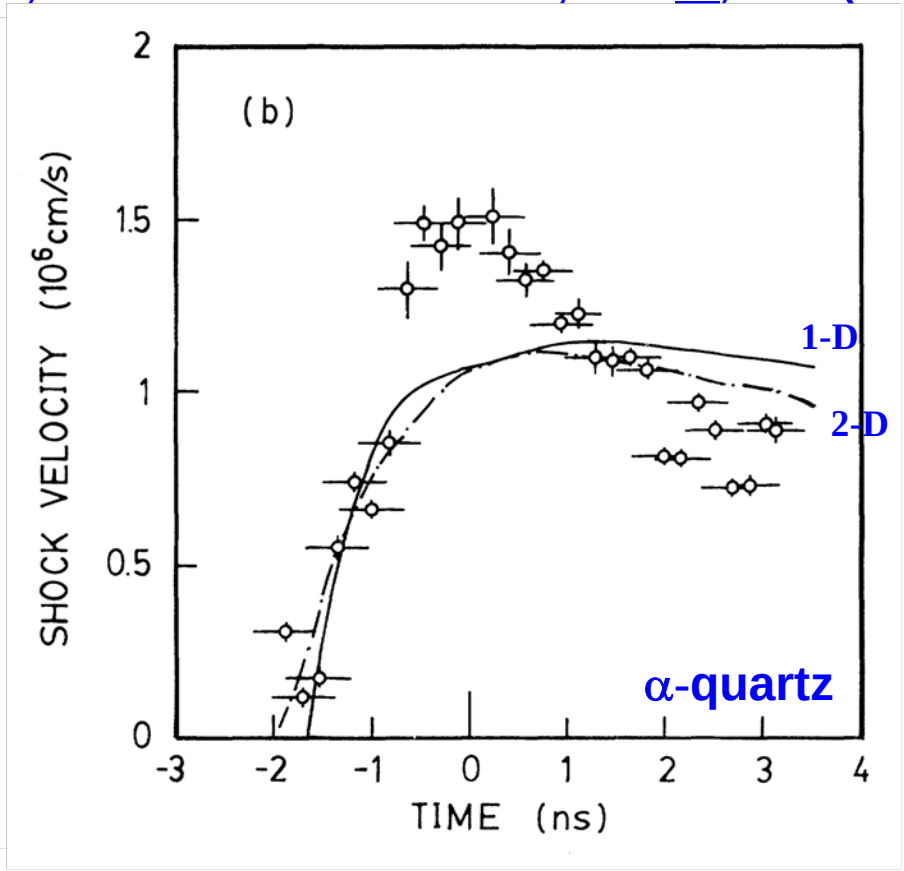
- Trajectory of shock front showed high-speed transient before relaxing to an asymptotic shock speed
- Peak transient speed higher than 1-D or 2-D predictions

A. Ng, P. Celliers and D. Parfeniuk, PRL 58, 214 (1987)

A. Ng, B.K. Godwal, J. Waterman, L. DaSilva, N.W. Ashcroft & R. Jeanloz, PRB 44, 4872 (1991)





Anomaly was found in quartz but not NaCl

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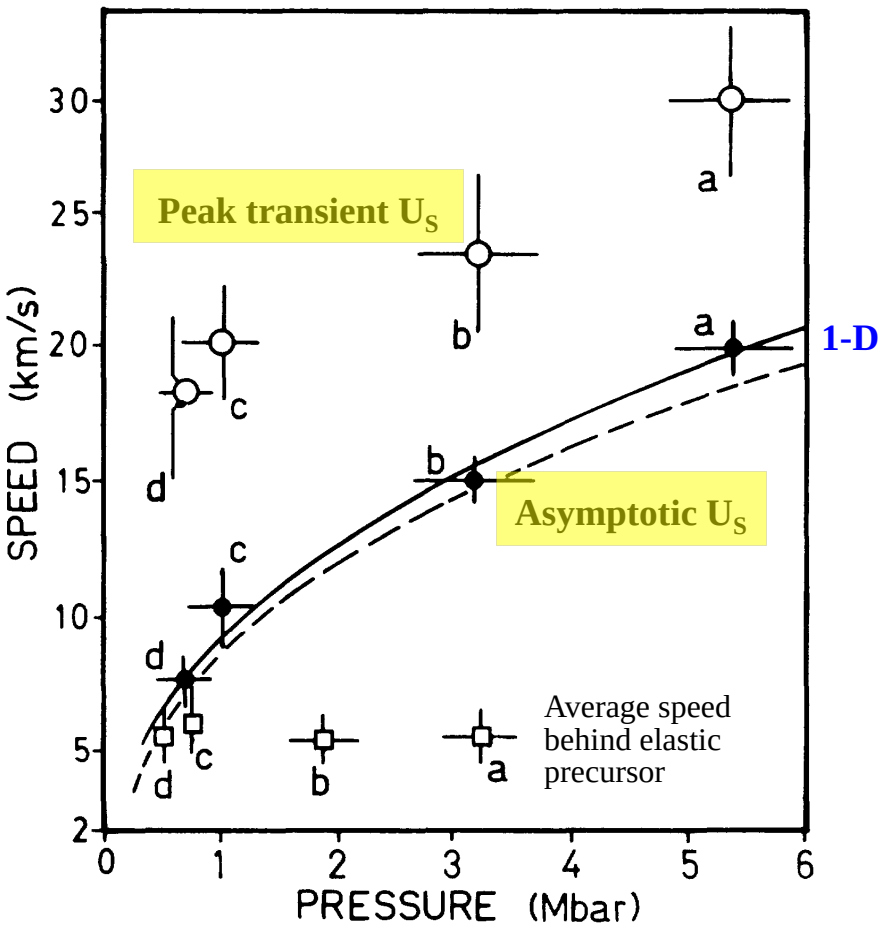
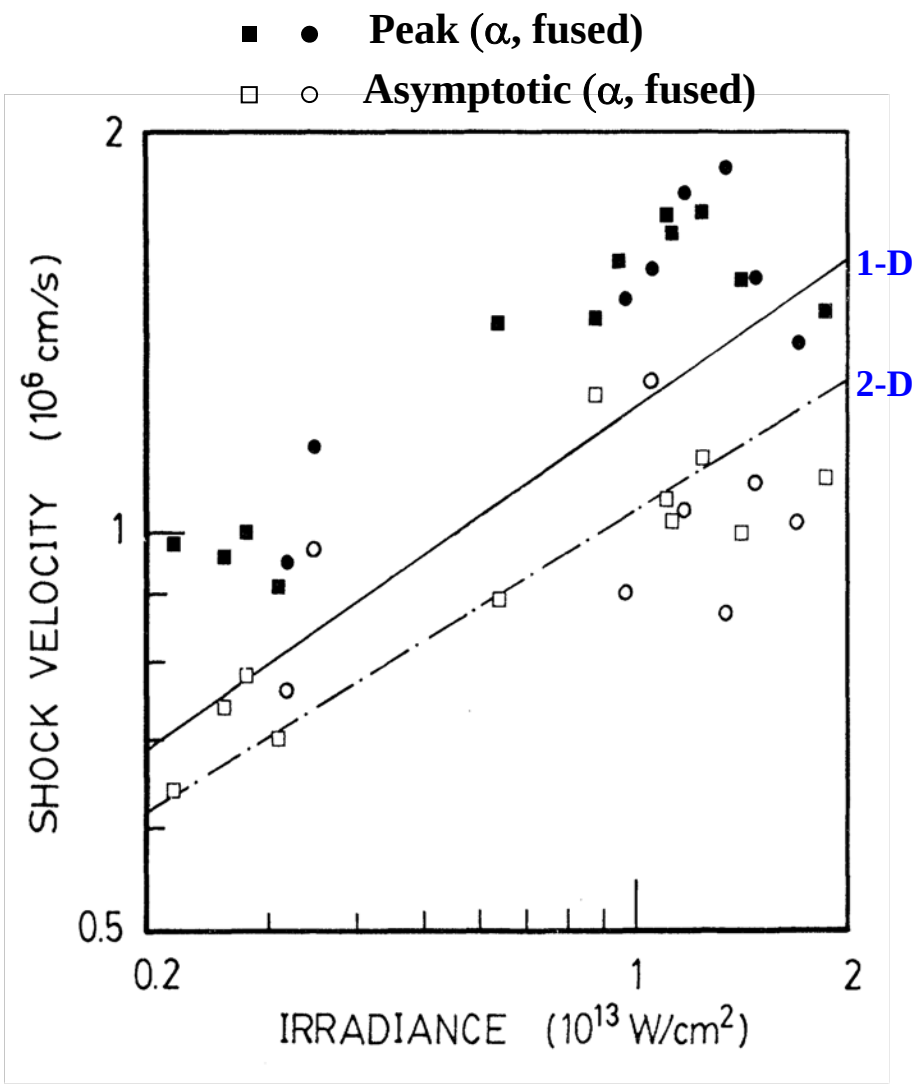
- **NaCl was used as a control for testing radiative preheat and phase transition effects**

Fused quartz





A conjecture for the observed anomaly is kinetic effect of phase transition in quartz

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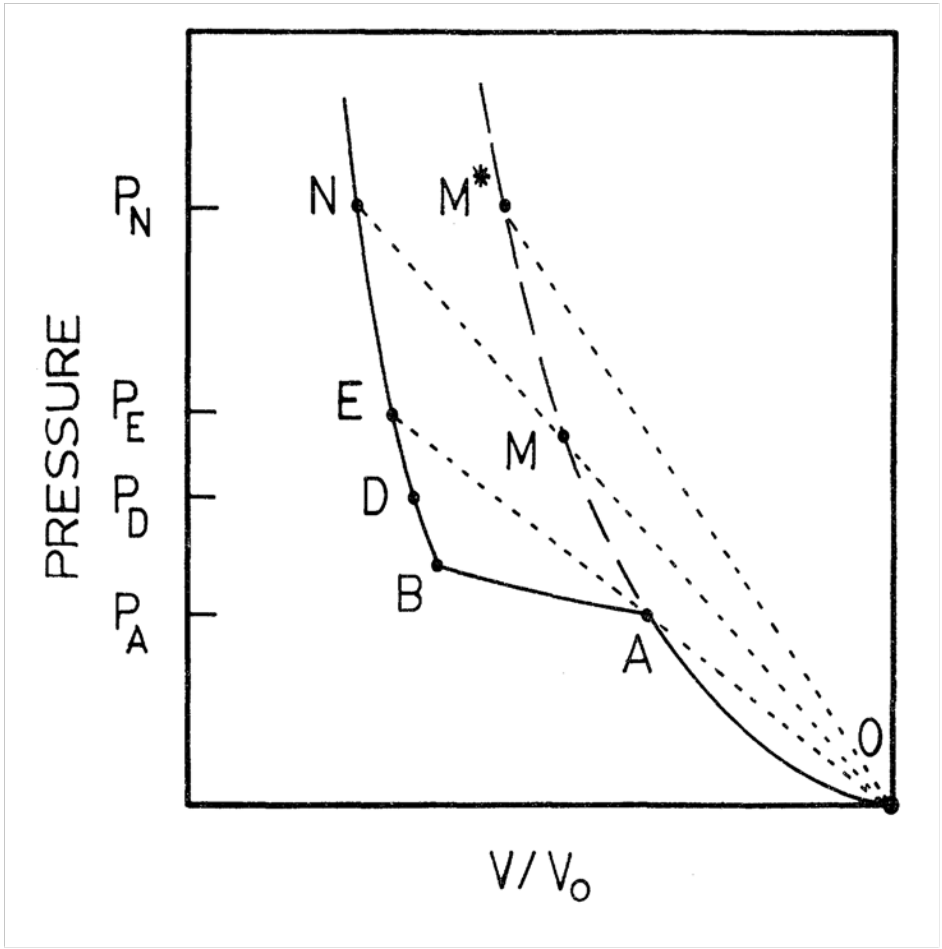
- **Quartz exhibits a large volume change at 0.1-0.3 Mbar on the Hugoniot due to the quartz-Stishovite transition**



Equilibrium behavior

Up to P_A - Single shock wave
P_A to P_E - Two wave structure
Above P_E - Coalesced single shock

Plausible overdriven behavior

At P_N, material at shock front initially responds in original phase forming state M* with U_S governed by the slope of OM

It then relaxes to equilibrium state N where U_S is governed by slope of ON

Another way to view the anomaly is the picture of a quasi-Hugoniot on P-V plane

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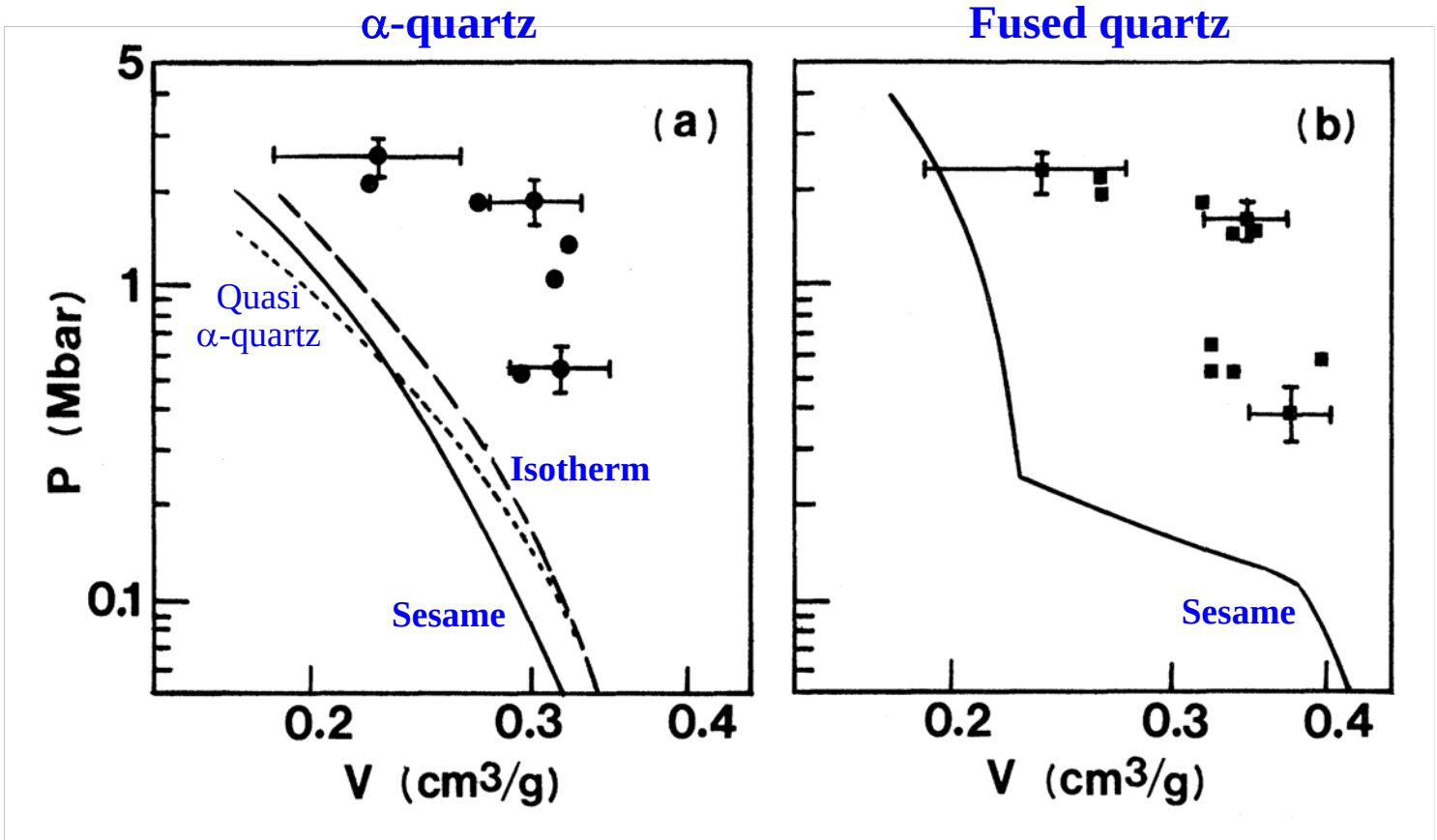
- **Transient shock speed U* combined with pressure P* from hydro simulations to yield compression V^*/V_0**
- **Discrepancy in pressure is due to entropy increase in nonequilibrium phase (Ashcroft)**



We have also inferred a rate-dependent phase transformation time in quartz

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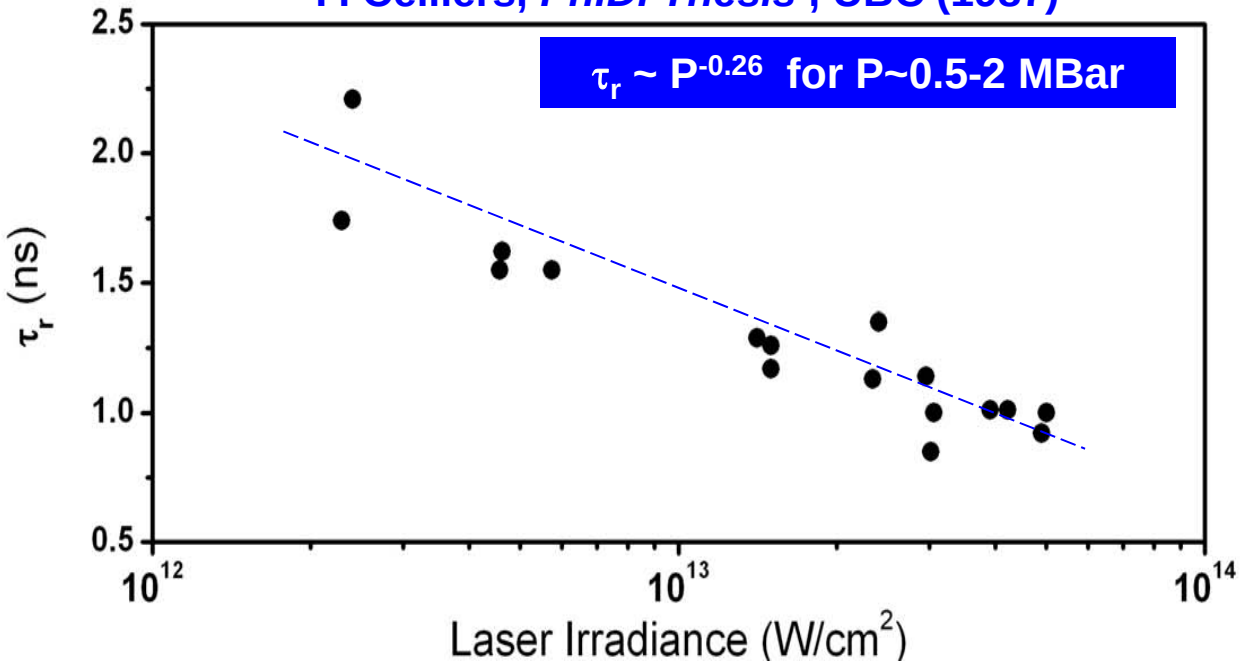
P. Celliers, *Ph.D. Thesis* , UBC (1987)



- **Much longer transformation times seen in other materials**
  - **Relaxation times of 0.05-0.3μs reported for α-ε transition in iron**
    - **S.A. Novikov *et. al*, JETP 1965; L.M. Barker *et. al*, JAP 1974; Forbes *et. al*, Phys. Soc. of Japan 1974)**
  - **Relaxation time of ~0.6μs for solid-solid transition in antimony**
    - **R.H. Warnes, JAP 1967**
  - **A transformation in KCl was observed to complete in 0.04μs**
    - **D.B. Hayes, JAP 1974**

The behavior of shocked quartz is tantalizing but needs confirmation

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- **How can we confirm the observed anomaly?**
  - **Probing shock propagation in quartz with VISAR**
  - **Probing shock propagation driven by sources other than lasers**
  - **Probing shock propagation in other phase transforming material**

These also led to broader questions

- **What is the effect of electron-ion equilibration on the Hugoniot melting point?**
- **What is the thermodynamic trajectory for transition of a quiescent state to a shocked state across the shock front?**
- ***What other discoveries will emerge in non-equilibrium shock physics?***

I hope that

- **There will be new interest in finding answers to all these questions**
- **Independent complementary experiments will be performed using shock waves generated by sources other than lasers**