SAND2015-3747D

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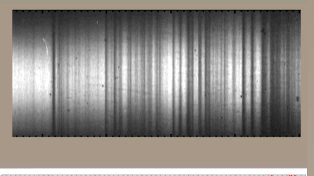
Stellar interior opacity measurements

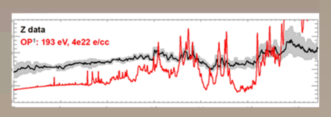
Z iron opacity experiments refine our understanding of the sun.

- Solar interior predictions don't match helioseismology
  - → Arbitrary 10-20% opacity increase would fix the problem, but is this the correct explanation?

- Z experiments have measured iron plasma opacity at nearly solar convection zone base conditions
  - → Experiment temperature is the same as in sun, density within a factor of 2



- Opacity models disagree with measurements at near-solar-interior conditions
  - → The solar Rosseland mean opacity is ~ 7% higher using Z iron data instead of OP calculations



The measurements imply photon absorption in high energy density matter is different than previously believed

Bailey et al., *Nature* 2015

The importance of stellar opacity was recognized nearly a century ago, but no laboratory measurements have been done up to now. Why?

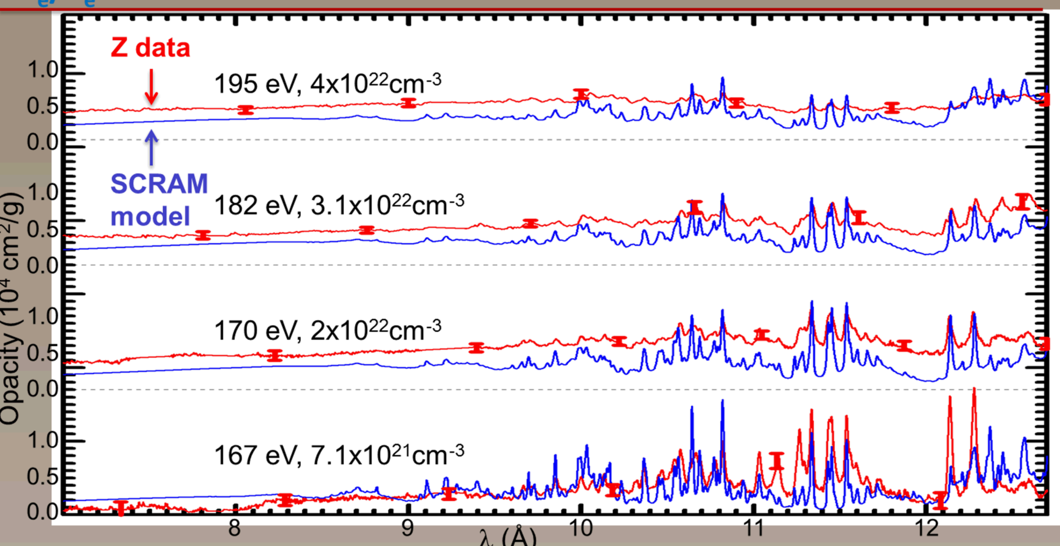
Eddington, "The Internal Constitution of the Stars", 1926

High transmission accuracy is needed since τ = -ln (T)

High accuracy requires:
Macroscopic samples uniformly heated to stellar interior conditions
Backlight bright enough to overcome emission at stellar interior temperatures

Stellar opacity measurements are possible for the first time:
MegaJoule class facilities like Z and NIF
3 decades of opacity research at smaller scale facilities to hone our approach
Advanced plasma diagnostic techniques

"Best Effort" opacity models "match" the iron data at lower T_e/n_e conditions but not at conditions near the solar CZB



At high temperature , density, calculations are generally lower than the data

The serious implications of this research mandate scrutiny of random and systematic uncertainties

Random error determination: average many spectra from multiple experiments

Systematic error evaluation:
Experiment tests
Postprocess benchmarked simulations

Eleven different potential systematic errors were investigated:

Sample contamination
Tamper shadowing
} potential increase for inferred opacity

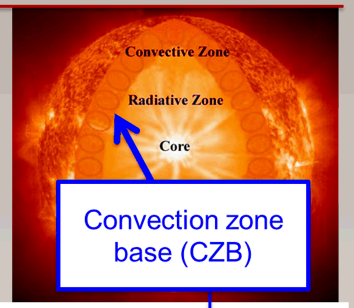
Fe self emission
Tamper self emission
Extraneous background
} potential decrease for inferred opacity

Sample areal density errors
Transmission errors
Spatial non-uniformities
Temporal non-uniformities
Departures from LTE
Plasma diagnostic errors
} potential increase or decrease for inferred opacity

None of the eleven possible errors investigated up to now explain the discrepancy

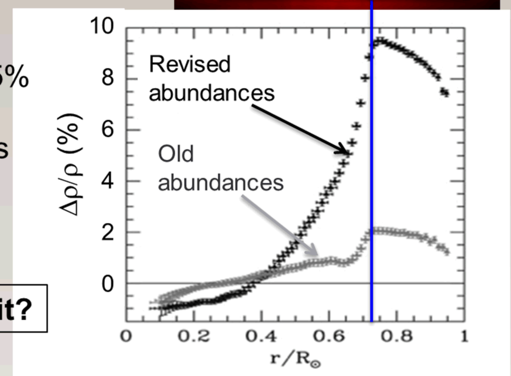
Standard solar model predictions of the solar structure disagree with helioseismology

- Standard solar model (simulation)
  Inputs:
  - Abundance
  - EOS
  - Opacity
  - Etc.
- Helioseismology (measurements)



- Solar abundance revision [Asplund 2005]
  C, N, O, Ar, Ne → lowered by 35-45%
- Now, standard solar model disagrees with helioseismic measurements

CZB location: 1σ → 13-30 σ



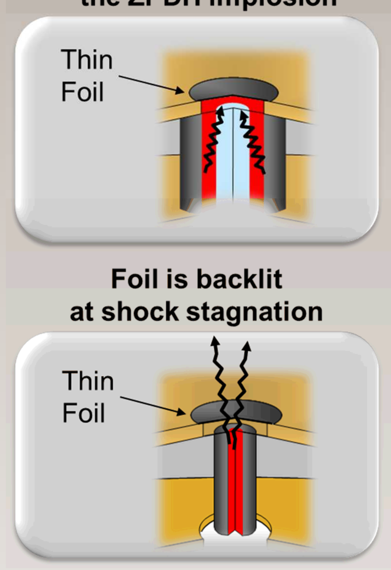
Are opacity model errors the culprit?

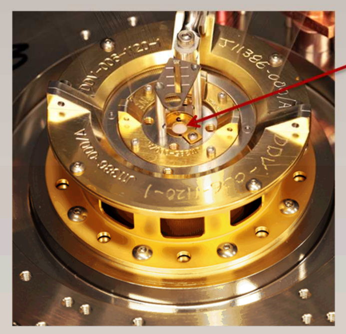
S. Basu *et al*, Physics Reports **457**, 217 (2008). M. Asplund *et al*, Annu. Rev. Astro. Astrophys. **43**, 481 (2005).

The ZPDH radiating shock is used to both heat and backlight samples to stellar interior conditions.

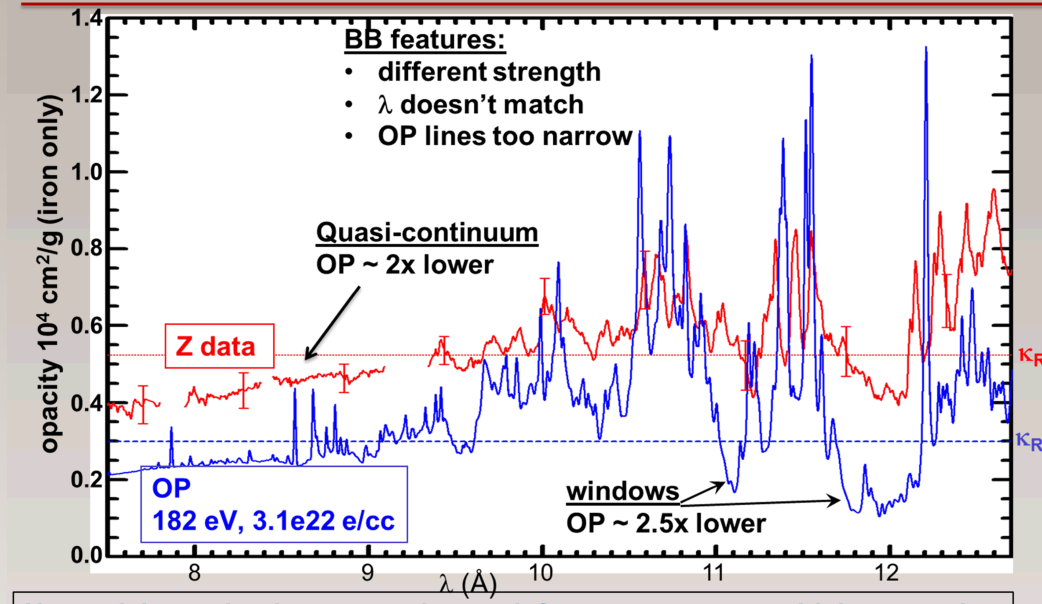
Foil is heated during the ZPDH implosion

Foil is backlit at shock stagnation





The OP opacity model is used in solar models but it disagrees with Z measurements at solar CZB conditions



No model examined up to now has satisfactory agreement with iron opacity measured at near-CZB conditions

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What are the hypotheses for the discrepancy and how can we test them?

Hypotheses:
1) Despite all our effort, iron measurement is flawed somehow
2) Photon absorption is shifted from long λ to short λ by a process that is as yet undetermined
3) Models have difficulty predicting opacity for open L-shell configurations
4) Models have difficulty predicting highly excited configurations

Tests:
A) Z experiments with lower and higher atomic number elements
B) Z experiments with lower and higher temperature and density
B) Experiments on a different platform (NIF)

If our opacity measurements are correct, we must revise our understanding for atoms in HED plasmas

- Measured iron opacities are 30-400% higher than theory predicts
- Opacity model accuracy reflects how well we understand atoms in plasma

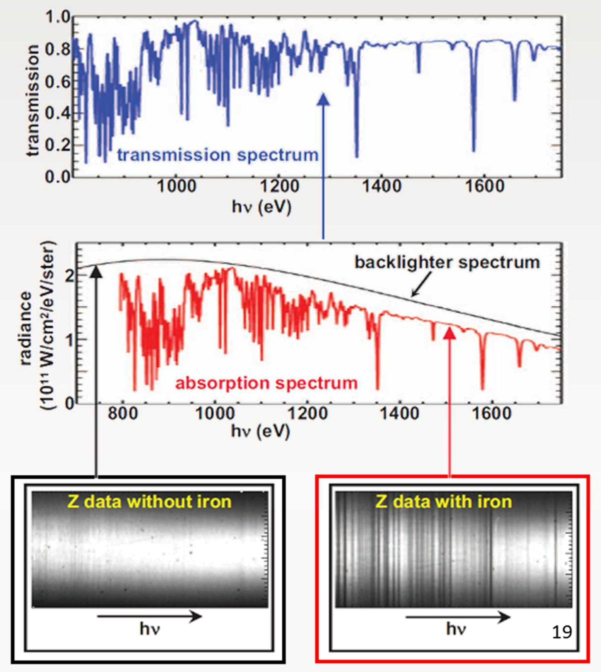
Applications include numerous HED plasmas:

- Solar opacity, composition, structure, and evolution are inter-connected
- Solar physics calibrates many other objects. Therefore the measurements alter our understanding of every main sequence star in the sky, including exoplanet host stars
- The measurements imply likely revisions for ICF capsule dopants

These serious consequences mandate continued effort

- We invested the last 2 years investigating possible errors and refining results
- The major conclusions survived this scrutiny
- New experiments are testing hypotheses for the model-data discrepancy

Transmission is inferred by dividing the attenuated spectrum by the unattenuated spectrum.



The measured pure iron Rosseland mean opacity is higher than calculated

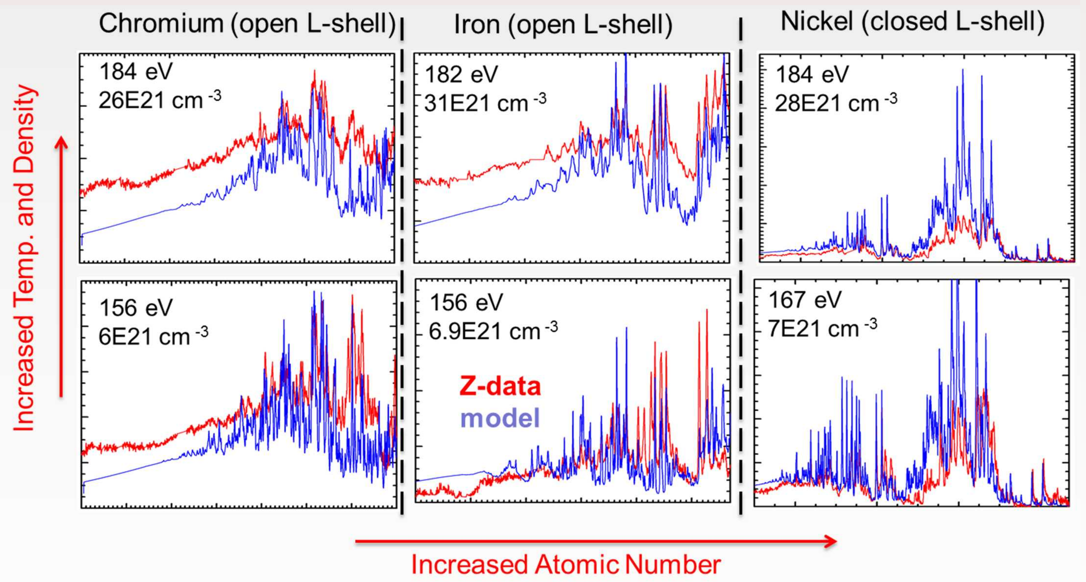
Model	experiment/model ratio Rosseland Mean
OP	1.75
OPAS	1.53
ATOMIC	1.75
SCO-RCG	1.57
SCRAM	1.67

This comparison:
1) Is for the 182 eV, 3.1x10^{22} electrons/cc conditions
2) uses only the measured wavelength range
3) accounts for the measured instrument resolution

- A *solar mixture* plasma using Z iron data has ~ 7% higher Rosseland mean opacity than using OP iron
- A 7% Rosseland increase partially resolves the solar problem, but the measured iron opacity by itself cannot account for the entire discrepancy
- Other elements and regions deeper in the sun could contribute

We will untangle the complex opacity issues through precise measurements across a range of T_e, n_e, and Z.

fewer L-shell vacancies, lower excited state populations



Increased Atomic Number

This work is a collaboration between seven institutions involving more than twenty scientists

Los Alamos National Laboratory EST. 1943
PRISM Computational Sciences, Inc.