HEDLP Workshop
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Laboratory Astrophysics at Z:
Stellar Interior Opacities

stellar interior iron transitions

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Modern HED facilities can provide essential stellar physics opacity knowledge.

Stellar structure depends on opacities.

- Predictions of the best studied star, our sun, do not agree with observations.
- Solar structure depends on opacities that have never been measured.

Challenge: create and diagnose stellar interior conditions on earth.

- Z opacity experiments reach T ~ 156 eV.
- High T enables first studies of iron transitions important in stellar interiors.
- New generation of HED facilities might simultaneously reach stellar density.
Modern solar models disagree with observations. Why?

- Measured boundary $R_{CZ} = 0.713 \pm 0.001$
- Predicted $R_{CZ} = 0.726$
- Thirteen $\sigma$ difference

"The CZ problem"

- Boundary location depends on radiation transport
- A 10-20% opacity change solves the CZ problem.
- This accuracy is a challenge – experiments are needed to know if the solar problem arises in the opacities or elsewhere.
To understand stars we need accurate opacities for mid-Z atoms at $T_e > 150$ eV and $n_e > 10^{22} \text{ cm}^{-3}$

Opacity Project calculations at bottom of solar convection zone
$T_e=193$ eV, $n_e=1x10^{22} \text{ cm}^{-3}$

- K-shell oxygen, K-shell neon, and L-shell iron are important at the CZ base
- The complexity of L-shell iron demands special scrutiny
- The importance of any single element is diluted by the mixture

Example:
Changing Fe L-shell by 1.5x causes ~11% change in total mean opacity
Opacity experiment challenges grow as temperature and density increase.

Comparison of unattenuated and attenuated spectra determines transmission:

\[ T = \exp \left( -\kappa \rho x \right) \]

At high temperature:
More energy in heating x-rays is required to produce uniform conditions
A brighter backlighter is required to overwhelm the self emission.
Z opacity experiments reach $T \sim 156$ eV, two times higher than in prior Fe research.

Fe + Mg at $T_e \sim 156$ eV, $n_e \sim 6.9 \times 10^{21}$ cm$^{-3}$

- Mg is the “thermometer”, Fe is the test element

J.E. Bailey et al., PRL 99, 265002 (2007)
Opacity experiment priority: produce the charge states found in stellar interiors

- Transitions in Fe with L-shell vacancies are important in the sun
- Laboratory experiments must produce high enough temperatures to ionize Fe into the L shell

The charge state distribution depends on $T_e/n_e$ and it strongly affects both bound-bound and bound-free transitions.
Modern detailed opacity models are in remarkable overall agreement with the Fe data.
The OP model used in solar research predicts Fe L-shell opacity that is too low at Z conditions.

OP Rosseland mean is ~ 1.5x lower than OPAS at Z conditions. If this difference persisted at solar conditions, it would solve the CZ problem.
Discrepancies at Z conditions raise a caution flag for solar opacities

At the base of the convection zone (T=193 eV, $n_e=10^{23}\text{cm}^{-3}$):
Iron frequency-dependent opacities possess some differences.
But Rosseland mean opacities are not significantly different, even though they disagree at Z conditions.
Why?

Red=OP - $\kappa_R=2606 \text{cm}^2/\text{g}$
Green=OPAS - $\kappa_R=2646 \text{cm}^2/\text{g}$
Blue = OPAL - $\kappa_R=2731 \text{cm}^2/\text{g}$
Experiments at higher density are a logical next step in stellar opacity research

We need to overcome the desire of the sample to expand when it is heated!

Increased tamping

Employ large low Z samples with dilute Fe concentration

Deliberately shock sample

Probe dynamic hohlraum interior

All options will likely require the greater heating x-rays and brighter backlighting available on the refurbished Z or the NIF
Modern HED facilities can provide essential stellar physics opacity knowledge

JB’s Prioritized list of new research for stars:
1. Iron L shell at density and temperature high enough to test Stark broadening and continuum lowering physics ($n_e \sim 10^{22} \text{ cm}^{-3}$, $T_e \sim 160 \text{ eV}$).
2. Effect of mixed low-Z and mid-Z elements (ion dynamics, influence on wavefunctions)
3. Oxygen and neon.

JB’s Prioritized list of new research for IFE:
1. Cu and Ge L shell
2. Effect of mixed low Z and mid Z