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Abstract

We propose an experiment to test opacity models for stellar atmospheres. Particularly important is to perform experiments at very low density and temperature where line shape treatments give large differences in Rosseland mean opacities for astrophysical mixtures, and to test the range of validity for the unresolved transition array treatments. Experimental requirements are ultra high spectral resolution combined with large homogenous plasma sources lasting tens of nanoseconds, and with Planckian radiation fields. These requirements dovetail nicely with emerging pulsed power capabilities. We propose a high resolution measurement of the frequency dependent opacity, for ultra low density iron plasmas in radiatively driven equilibrium plasmas.

Models for the opacity of stellar mixtures play an important role in astrophysics since the radiative energy transport in stars governs stellar structure and evolution. The opacity models are complex, requiring knowledge of atomic structure, level populations, spectral line shapes, and plasma interactions. Simplifying assumptions and approximations are often used owing to the enormous amount of atomic data required, and to the intractable nature of the many-body problem. Until recently, stellar models relied on theoretical opacity calculations produced primarily at Los Alamos[1]. While these models were adequate to

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explain the main features of stellar evolution, some problems persisted. The situation was improved with the introduction of new calculations using the OPAL[2] opacity code developed at LLNL. These new opacities have led to the resolution of long standing puzzles in stellar pulsation.[3]

Direct experimental verification of the opacity models has also been pursued at LLNL using the NOVA laser[4-9]. In this campaign, an exceptional amount of effort has gone into simultaneously measuring the opacity, the temperature and the density of the plasma on each experiment, These experiments provided highly constraining benchmark data that significantly and unambiguously challenged the capabilities of standard opacity codes. The comparisons between theory and experiment clearly demonstrate the shortcomings of the older opacity calculations, but improvements in the experiments are necessary in order to discriminate between modern opacity codes. Particularly important is to perform experiments at very low density and temperature where line shape treatments give large differences in Rosseland mean opacities for the astrophysical mixtures.[10] An astrophysical opacity measurement using pulsed power drivers is proposed to address the ultra low density iron opacity important to stellar atmospheres.

Overview

The stellar structure is affected by the opacities in the stellar interior which set the radial temperature and density distributions needed to maintain the equilibrium radiative heat flux. A strong dependence of opacity on stellar depth allows regions that are unstable to convection, providing both an additional energy transport mechanism and mixing within stars. Features of the depth dependence of the opacity can even lead to stellar pulsation, where large amplitude modes of oscillation are driven by thermal gradients within the star, giving a periodic variation in radius and brightness.

The most common types of variable stars occur in a narrow band of the Hertzsprung-Russell HR diagram called the Cepheid instability strip which is shown in Figure 1. All stars inside this band in the HR diagram pulsate. With periods between two and fifty days, these stars change their radii between 5 and 20 percent, and their light output by factor of order 2. A relationship between the variable star luminosity and its period has been established for the Cepheid variable stars. This allows highly luminous Cepheid variable stars to serve as an extragalactic distance indicator.

These classical Population I Cepheids are supergiants, with radii of order 20 -200 solar radii. During advanced stages in their evolution, these massive stars may traverse the Cepheid instability strip several times during blue loop excursions when new nuclear reactions become possible in their cores. Depending on assumed stellar compositions, the stellar evolution models predict masses (4 to 13 solar masses) and corresponding luminosities likely for Cepheid variable stars. Because these stars pulsate, observations can test critical aspects of these models. The frequency of oscillation of the fundamental and higher modes, as well as the shape and relative phase of the light and velocity curves depend upon the density and temperature stratification within the star, and give information on stellar structure and mass. These features in turn are sensitive to opacity models in a regions accessible to laboratory experimentation.

Opacity theory and experiments

Until the early 1990's stellar structure and pulsation models that matched observations gave Cepheid masses much lower than were permitted by stellar evolution calculations. These discrepancies have since been resolved with the OPAL opacity code through a better treatment of the metal contribution to astrophysical opacity models. The OPAL predictions since been confirmed by other methods for calculating detailed opacities. The improved opacity model solved several outstanding problems simultaneously. It provided the kappa-mechanism for the pulsation instability in β Cephei stars. These B type stars are not positioned in the Cepheid instability strip. It reconciled pulsation and stellar evolution masses for the double-mode Cepheids, the δ Scuti stars, the Bump Cepheids, and the RR Lyrae variables. The successes of the OPAL code in solving some long outstanding problems in astrophysics is a rather indirect test of the validity of the model, especially given the complexity of the stellar models, and the uncertainties in stellar chemical composition. The opacity calculations still embody many approximations and they should be confirmed at astrophysically relevant conditions.

Direct experimental verification of the opacity models has been pursued at LLNL using the NOVA laser. The 16 kJ, 353 nm heating laser creates x-rays that radiatively heat tamped targets. An imaging XUV spectrometer produces a spectral resolved shadowgraph of the target using another NOVA beam to produce a x-ray backlighting plasma. To date, NOVA experiments have provided highly resolved, frequency-dependent opacities for several mid-Z elements in local thermodynamic equilibrium (LTE) at temperatures from 10-60 eV, and densities around 1/1000 normal[4-9]. In this campaign, an exceptional amount of effort has gone into simultaneously measuring the opacity, the temperature and the density of the plasma on each experiment, These experiments provided highly constraining benchmark data that significantly and unambiguously challenged the capabilities of standard opacity codes.

Limits on density imposed by sample size and a requirement to obtain LTE conditions through collisional processes has restricted previous NOVA experiments to densities above 10^{-2} g/cc. Particularly important is to extend proven NOVA experiments to very low density and temperature where line shape treatments give large differences in Rosseland mean opacities for astrophysical mixtures, and to test the range of validity for the unresolved transition array treatments. Experimental requirements are ultra high spectral resolution combined with large homogenous plasma sources lasting tens of nanoseconds, and with Planckian radiation fields. These features are illustrated in Figure 2 and 3. These requirements dovetail nicely with emerging pulsed power capabilities. We propose and are designing a high resolution measurement of the frequency dependent opacity, for ultra low density iron plasmas in radiatively driven equilibrium plasmas. We are examining the 200 kJ Saturn pulsed power facility to provide the large, homogeneous, long-lived radiation environment needed for these measurements. This is illustrated in figure 4. We will use techniques similar to those developed for the laser driven experiments, but at much higher spectral resolution.

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