(U) Calculations of spectral outputs

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Abstract

In an effort to help explain the results of recent opacity experiments at the Sandia Z facility [1,2] we have begun work on forward modeling their spectral outputs in order to examine the assumptions about the behavior of the employed opacity targets. To that end, in this work we present preliminary verification and validation results of our new spectral postprocessor to hydrodynamics simulations [3,4].

Introduction

Opacities are an essential ingredient in theoretical models and computer codes applied to various types of plasmas of astrophysical interest. More specifically, Rosseland mean opacities are needed to account for the transfer of energy in star interiors [5] as well as in applications relying on radiation-hydrodynamics simulations [6], such as Inertial Confinement Fusion (ICF). Since experimental measurements of opacities are rather scarce, covering limited regions within the periodic table and ranges of plasma conditions, theoretically calculated opacities have been the chief source of opacity data for such models. Therefore, validation of computed opacities against any available experimental measurements is essential for developing confidence in the models used to calculate them. In the past, a few successes in opacity validation have been reported (see, for example, [2]). More recently, however, higher-than-expected iron opacities were reported based on measurements conducted at Sandia's Z facility [1]. So far, this discrepancy remains unexplained, since no theoretical model has provided a generally accepted explanation for the results of these experiments as of the time of this publication.

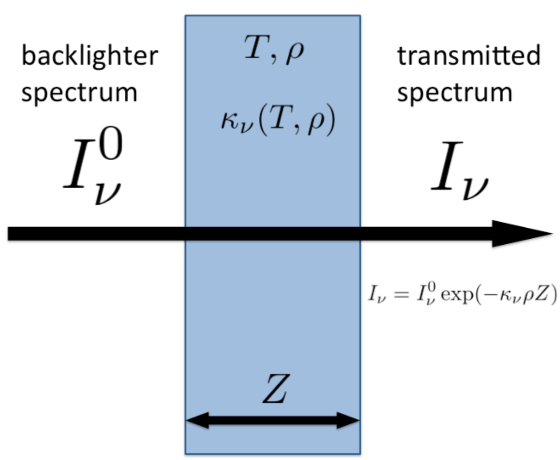

Fig. 1. – Schematic of an ideal opacity experiment.

Whole-experiment modeling

A schematic of an ideal opacity experiment is presented in Fig. 1. A slab of the studied material is prepared with known, spatially uniform temperature T, density ρ, and thickness Z. It is backlit with a well-characterized spectrum of electromagnetic radiation $\boldsymbol{I_\nu^0}$, which is absorbed and scattered by the sample. Furthermore, the sample itself is expected to contribute no appreciable self-emission to the measured intensity $\boldsymbol{I_\nu}$. The opacity of the material $\boldsymbol{\kappa_\nu}$ can then be extracted from the measured transmitted spectrum $\boldsymbol{I_\nu}$ according to

$$\kappa_\nu = \frac{\ln \frac{I_\nu^0}{I_\nu}}{\rho Z} \quad . \tag{1}$$

Such an arrangement is challenging to achieve in actual experiments. If the state of the probed sample deviates from this ideal, while the opacity continues to be retrieved from the measured data via Eq. 1, the inferred value may not adequately represent the real opacity. To that end, we have decided to evaluate the validity of these idealized assumptions (upon which Eq. 1 rests) by modeling the entire experimental setup via radiation-hydrodynamics modeling and postprocessing the results with a spectral code. Preliminary results [7] offered a potential explanation by suggesting that a hydrodynamic tilt of the sample could be responsible for the reduced transmission by increasing the effective absorption path length Z, without the need to modify our computed opacities [8]. These simulations, however, were only 2D and they did not include the possible effects of the magnetic fields that are known to be present in these experiments, and thus our modeling ought to be repeated with a 3D magnetohydrodynamics (MHD) code before we can draw any firmer conclusions. In the meantime, we embarked on the verification and validation (V&V) of the new spectroscopic postprocessor code FESTR [3,4] that is being adopted for our whole-experiment modeling of the Sandia opacity experiment. The results of two such tests are the subject of this publication.

Emergence of the Planckian

In 1D planar geometry and a material of uniform density $\boldsymbol{\rho}$ the steady-state radiation-transport equation

$$\frac{dI_\nu}{dz} = \epsilon_\nu - \rho\kappa_\nu I_\nu \tag{2}$$

has the analytic solution

$$I_\nu = I_\nu^0 e^{-\rho\kappa_\nu Z} + S_\nu (1 - e^{-\rho\kappa_\nu Z}) \tag{3}$$

in which the source function ($\boldsymbol{S_\nu = \epsilon_\nu/\rho\kappa_\nu}$) becomes Planckian at the material temperature under the assumption of local thermal equilibrium (LTE). If there is no backlighter (i.e., $\boldsymbol{I_\nu^0 = 0}$), then the emergent intensity $\boldsymbol{I_\nu}$ is entirely due to the self-emission from the material.

In that case Eq. 3 operates between two limits controlled by the optical depth, which is the ratio of the ray chord length Z to the photon mean free path. On the one hand, in the optically thick limit, the chord length Z is so large that the underlying spectral line structure characteristic of any chosen material is obliterated by the repeated absorption and reemission of photons of all frequencies $\boldsymbol{\nu}$, resulting in blackbody emission $\boldsymbol{S_\nu}$ that depends only on the temperature. On the other hand, in the optically thin limit, the thickness Z is so small that the material becomes transparent and the emergent specific intensity increases linearly with the chord length Z

$$I_\nu \to \epsilon_\nu Z, \tag{4}$$

retaining the spectral line structure of the adopted material. This behavior is successfully reproduced numerically by the FESTR code and shown in Fig. 2. In a general case the blackbody limit is gradually reached with an increasing thickness Z, with the rate of approach depending on the photon frequency $\boldsymbol{\nu}$; whereas line centers (high opacity) achieve their Planckian limit sooner, the valleys between the lines (low opacity) require a larger physical depth Z to achieve their own thermal limits.

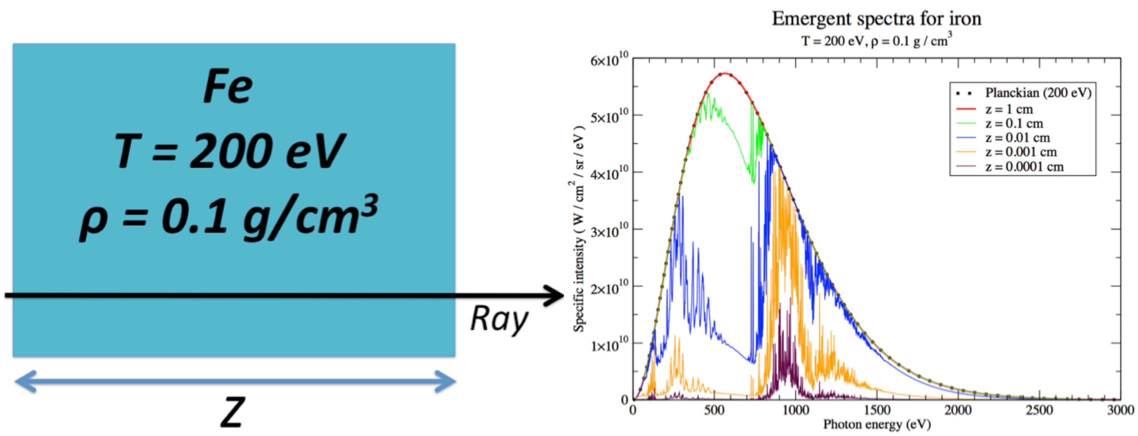

Fig. 2. – FESTR synthetic spectra using OPLIB opacities [4,8].

Thermal radiation is Lambertian

Once the radiation source becomes Planckian (e.g., the iron plasma with $Z = 1$ cm from Fig. 2), it will have the Lambertian characteristic of the signal strength depending on the cosine of the angle between the line of sight and the normal direction of an emitting aperture. We reproduce this expected behavior numerically with the FESTR code. To that end, we enclose an emitting blackbody in an opaque can with an opening and view this setup from various angles (see Fig. 3). For each angle of view, a detector integrates the radiation signals from a large collection of rays (a “Ray bundle” [3]). Rays that cut across the emitting aperture each contribute the Planckian marked with the red trace in Fig. 2; rays that hit the opaque enclosure contribute nothing. As the line of sight progressively deviates from the aperture’s normal direction, the number of contributing rays decreases in proportion to the cosine-like reduction in the aperture’s projected area (see Fig. 4).

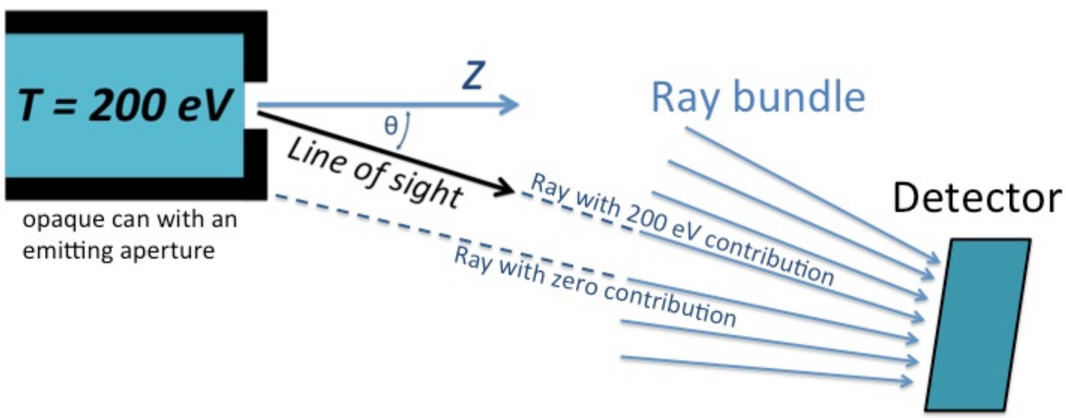

Fig. 3. – Geometry of the Lambertian test.

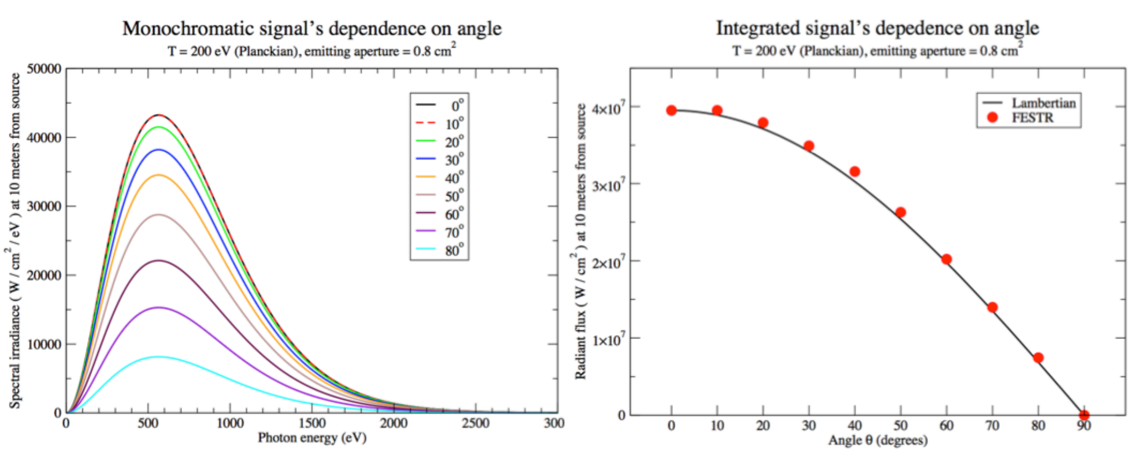

Fig. 4. – Signal levels for a blackbody emitting aperture viewed from various directions (1981 bundled rays were used to sample the materials).

With the expected angular dependence of the intensity confirmed, the numerically calculated peak value of the integrated signal level (in Fig. 4 at zero degrees) of approximately **4×10^7** W/cm^2 can also be computed analytically from the following considerations:

temperature (T): 200 eV (2.321 million Kelvin)

flux emitted by the aperture (σT^4): 1.6×10^{14} W/cm^2

radiance ($\sigma T^4/\pi$): 5.2×10^{13} W/cm^2/sr

source-detector distance: 1000 cm

detector area: 1 cm^2

solid angle spanned by the detector as seen from the emitting aperture: 10^{-6} sr

aperture radius: 0.5 cm

aperture area: 0.8 cm^2

flux at detector = radiance × aperture area × solid angle / detector area = **4×10^7** W/cm^2

Conclusions

The newly developed FESTR spectroscopic modeling code is now successfully passing a number of basic V&V tests. Therefore, we judge this code to be mature enough to be applied to whole-experiment modeling of the Sandia opacity experiments, as the requisite MHD simulations become available in the future. This work is expected to address one of the hypotheses proposed to resolve the outstanding mystery of the higher-than-expected opacities that were reported in recent experimental measurements.

Acknowledgements

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