Implicit Monte Carlo Methods for Three-Temperature Physics

Thomas Evans, Jeffery Densmore, CCS-2

The simulation of thermal radiation propagation ranks among the most difficult class of transport problems. These problems are highly nonlinear, and the fundamental unknown (the radiation intensity) can be a function of seven independent variables [in three dimensions (3-D)]. One of the most successful and widely used methods in thermal radiation transport is the Implicit Monte Carlo (IMC) method [1]. This method is a two-temperature (2T) scheme that includes radiation and material coupling where the matter is represented by a single temperature.

A more accurate description of the radiation and material coupling represents the ions and electrons by distinct, separate temperatures [2]. The resulting three-temperature (3T) equations for the time evolution of the radiation, electron, and ion energies include terms representing electron-ion coupling and conduction [3]. Conventionally, this system of equations is solved using radiation diffusion with operator-split conduction and coupling [4].

The objective of this study is to extend the standard IMC method to include 3T physics. Descriptions of matter that include separate energies for electrons and ions are important in high energy density physics applications and astrophysics [5]. We derive three methods for solving the 3T equations using IMC. The first method (FSIMC) uses the standard IMC technique to simulate radiation transport. The conduction and coupling terms are linearized and split into separate equations that are solved independently. A second method (SCIMC) uses a more robust splitting scheme in which half of the coupling is treated during the transport simulation. The conduction is split from the ion and electron equations and is solved subsequently. Afterwards, the second half of the coupling is solved. The third method (ECIMC) treats the conduction explicitly and includes all of the conduction and coupling in the linearization of the transport equation. This is a good approximation when the conduction timescales are much longer than the radiation-transport timescales. We expect this to be the case for most problems because the conduction timescales are related to the electron thermal velocity whereas the radiation moves at the speed of light. The resulting system has three equations: a Monte Carlo transport equation and two decoupled energy equations for electrons and ions.

We use Modified Equation Analysis (MEA) [6] to estimate the errors that result from operator splits and linearization. In short, MEA uses Taylor series expansions to convert from a discrete to continuous system of equations. The resulting set of *modified* equations consists of the original continuous system plus error terms. Figure 1 shows the results of each IMC method on a source-driven 3T test problem. Using MEA, we have plotted the magnitude of the error terms for this problem in Fig. 2. The error terms A and B dominate, and because these terms are only present in the SCIMC and FSIMC methods, they account for the improved accuracy of the ECIMC method illustrated in Fig. 1.

In this study we have presented three IMC methods for performing 3T radiation-transport calculations. We have shown that the ECIMC method is considerably more accurate than the SCIMC and FSIMC methods in problems where the ions and electrons are decoupled. The ECIMC method will only be viable in problems where the electron and ion conduction timescale is slow compared to the radiation timescale. In cases where the conduction timescale is of the same order as the radiation timescale, the SCIMC method is most optimal. Future work includes extending these methods to fully analyze the effects of radiation conduction and extension to multifrequency.

For more information contact Jeffery Densmore at jdd@lanl.gov

[1] J.A. Fleck and J.D. Cummings, *J. Comp. Phys.* **8**(3), pp. 313–342 (1971).
[2] M. Sincell, et al., *Shock Waves* **9**, pp. 403–411 (1999).
[3] J. Huba, *NRL Plasma Formulary*, Naval Research Laboratory, Washington, D.C., 2004.
[4] G. Olson and J.E. Morel, "Solution of the Radiation Diffusion Equation on an AMR Eulerian Mesh with Material Interfaces," Los Alamos National Laboratory report LA-UR-99-2949 (June 1999).
[5] T.D. Matteo, et al., *Mon. Not. R. Astron. Soc.* **291**, pp. L23–L27 (1997).
[6] D. Knoll, et al., *J. Comp. Phys.* **185**, pp. 583–611 (2003).

Funding Acknowledgements
NNSA's Advanced Simulation and Computing (ASC), Computational Physics and Methods Mission Capability Program, Transport Project.

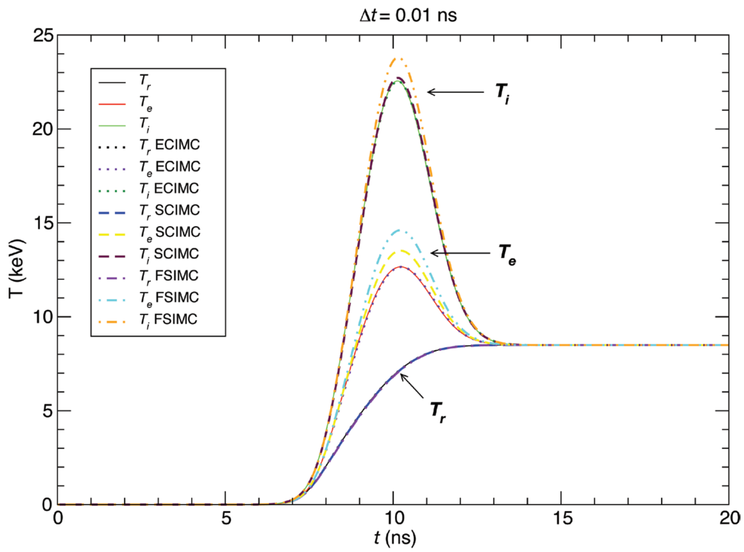

Fig. 1.
Comparison of three IMC methods on a Gaussian ion source problem. The ECIMC method is the most accurate.

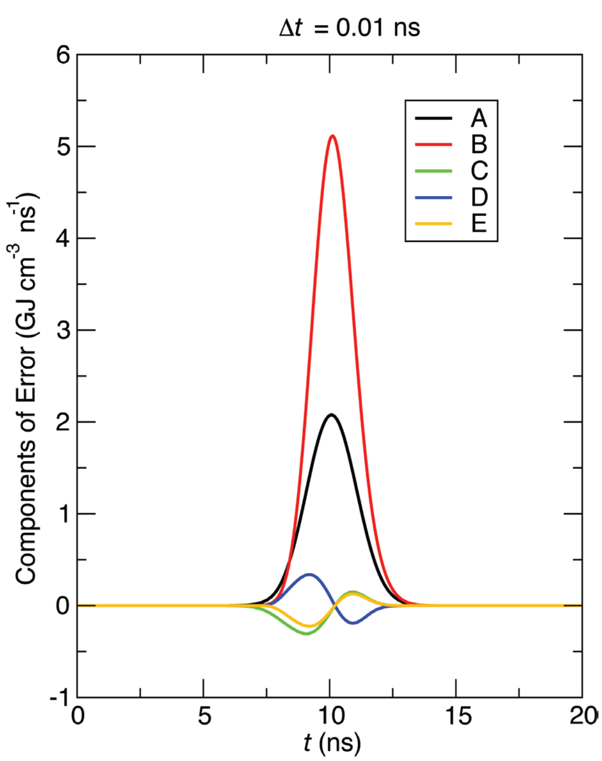

Fig. 2.
Magnitude of the error terms that result from the linearization and splitting strategies employed in the three IMC methods. The C, D, and E terms are present in all three methods. The A and B terms are only present in the SCIMC and FSIMC methods. The B term is twice as large in the FSIMC method (not plotted).