On the Application of a Hybrid Monte Carlo Technique to Radiation Transport in High-Velocity Outflow

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Abstract: Implicit Monte Carlo (IMC) is a stochastic technique for solving the nonlinear radiation transport equations[1]. Discrete Diffusion Monte Carlo (DDMC) is a stochastic diffusion method that is generally used to accelerate IMC for Monte Carlo (MC) particle histories in optically thick regions of space and energy[2]. The hybrid IMC-DDMC (HMC) method has recently been extended to account for multi-frequency and velocity effects[3,4]. We verify the accuracy of HMC with respect to a static material benchmark, a high-velocity manufactured benchmark, and pure IMC for problems involving non-gray opacity.

Introduction:

IMC and DDMC are of interest for application to astrophysical problems. IMC is a semi-implicit MC radiation transport method that models some absorption and emission as instantaneous "effective scattering". DDMC accelerates IMC in optically thick energy (or wavelength) groups and spatial cells by replacing many small scattering steps with fewer large "leakage" steps.

Discussion:

We have tested multi-group, 1D spherical HMC for use on static spatial grids and homologous velocity grids. We find that our implementation of IMC, DDMC, and HMC yield satisfactory agreement in the verifications below. For all problems presented HMC is significantly faster than pure IMC.

Acknowledgements:

We would like to thank Ernazar Abdikamalov, Allan Wollaber, and Jeffery Densmore for their exchanges. This work was supported in part by the University of Chicago and the National Science Foundation under grant AST-0909132.

References:

[1] Fleck and Cummings, "An implicit Monte Carlo scheme for calculating time and frequency dependent nonlinear radiation transport", J. Comput. Phys. 8, 313 (1971).
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[3] Abdikamalov, Burrows, Ott, Loffler, O'Connor, Dolence and Schnetter, "A new Monte Carlo method for time-dependent neutrino radiation transport", ApJ 755, 111 (2012).
[4]Wollaeger, van Rossum, Graziani, Couch, Jordan, Lamb and Moses (in press), "Radiation transport for explosive outflows: a multigroup hybrid Monte Carlo method", ApJS 210 (2014).

Static Material Tests:

A delta source in space and time is implemented in a non-dimensional problem (time in # of mean free times, space in # of mean free paths). A two level, picket-fence opacity distribution with very high contrast between opacity levels allows for a closed-form P_1 benchmark. P_1 is higher order than diffusion but still approximate. The picket-fence structure has groups of infinitesimal width.

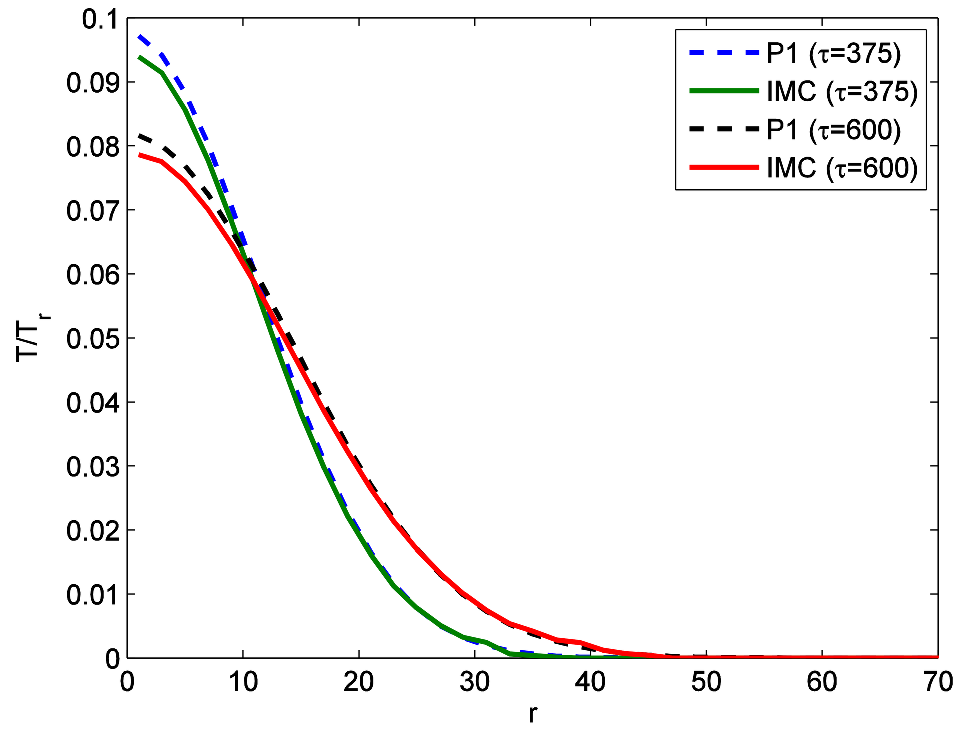

Figure 1: P_1 (dashed) and IMC (solid) unitless material temperature plotted over radial number of mean free paths. At 2 mfps per cell, HMC applies entirely IMC. The time evolution of the simulated result agrees with analytic prediction.

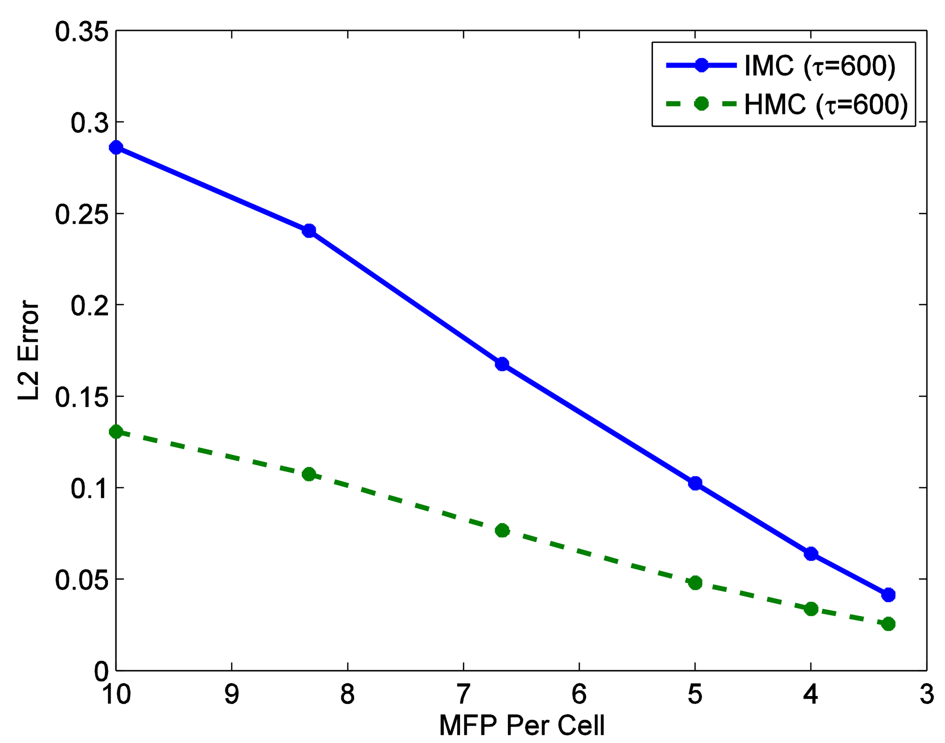

Figure 2: IMC (solid) and HMC (dashed) L_2 temperature error relative to the P_1 solution plotted over the number of mean free paths per cell. IMC contributes negligibly to the temperature in HMC for this problem. The error appears to be linear. The error for HMC is distinctively lower.

Manufactured Source Tests:

A multi-group source obtained with the Method of Manufactured Solutions (MMS) is implemented. The problem has 2 groups: the lower wavelength group has elastic scattering, the higher wavelength group has elastic scattering and absorption. This source must keep the radiation energy density and fluid temperature profiles constant; thus it counteracts redshift.

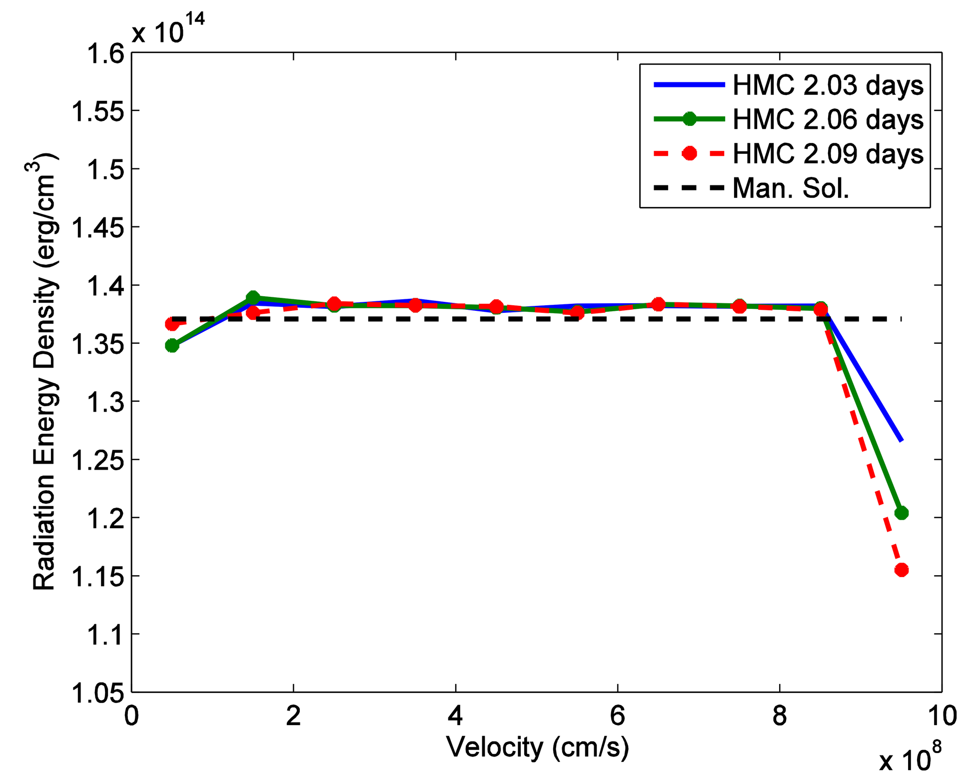

Figure 3: Manufactured (dashed) and HMC radiation energy densities at 3 different times (solid, dot-solid, dot-dashed). There is strong coupling through Doppler shift between the 2 groups of the problem. IMC is applied in the pure scattering group and DDMC in the mixed group. This test verifies HMC preserves the manufactured profile.

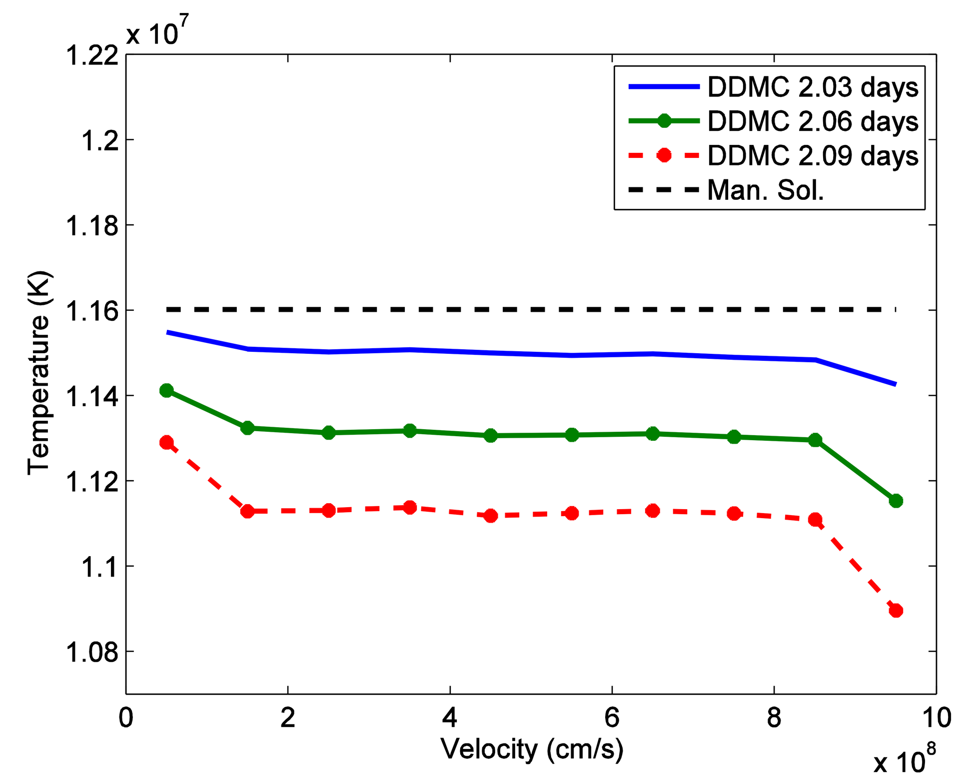

Figure 4: Manufactured (dashed) and DDMC material temperature at 3 different times (solid, dot-solid, dot-dashed). The manufactured source in the pure scattering group has been removed. The decreasing material temperature indicates that the pure scattering group is a source to the mixed group through Doppler shift, as expected.

Heaviside Source Tests:

A spherical Heaviside source non-zero over 4/5 of a 1e9 cm/s outflow is implemented. The group structures are tabulated:

	Groups g=1,3,5,7,9	Groups g=2,4,6,8,10
Figure 5	$\sigma_g = 0.13\rho$ cm^{-1}	$\sigma_g = 0.13 \times 10^{-4}\rho$ cm^{-1}
Figure 6	$\sigma_g = 0.13\rho$ cm^{-1}	$\sigma_g = 0.13 \times 10^{-7}\rho$ cm^{-1}

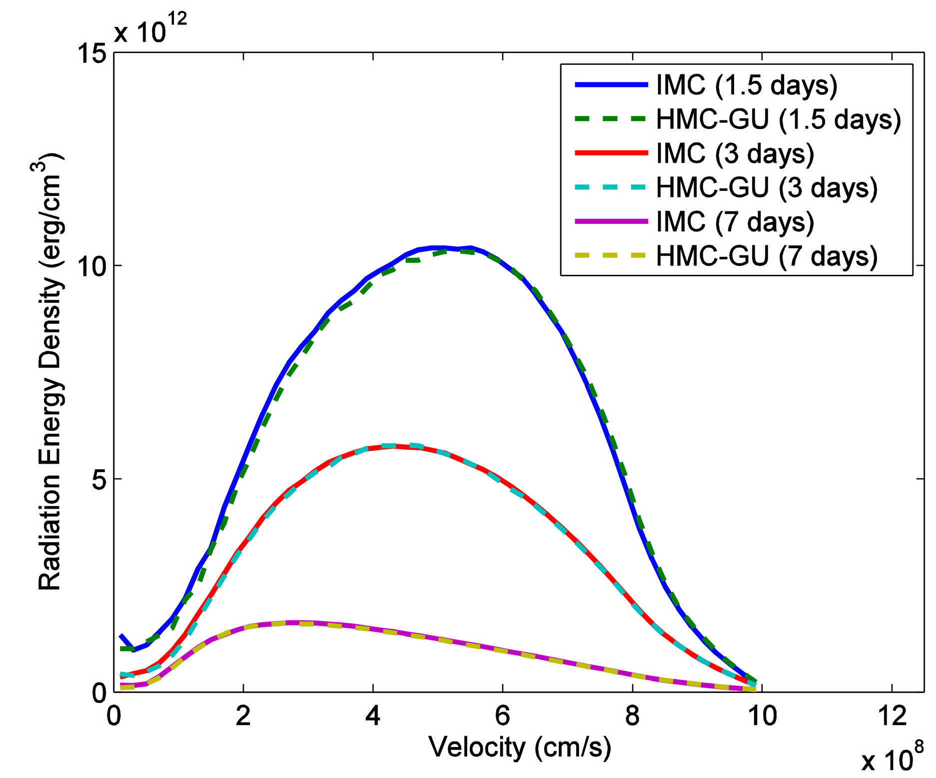

Figure 5: Radiation energy density for IMC (solid lines) and HMC (dashed lines) for 1e9 cm/s outflow and 1e4 disparity between opacities of adjacent groups. A three mfp threshold between IMC and DDMC makes HMC faster than IMC by factor of 3.36.

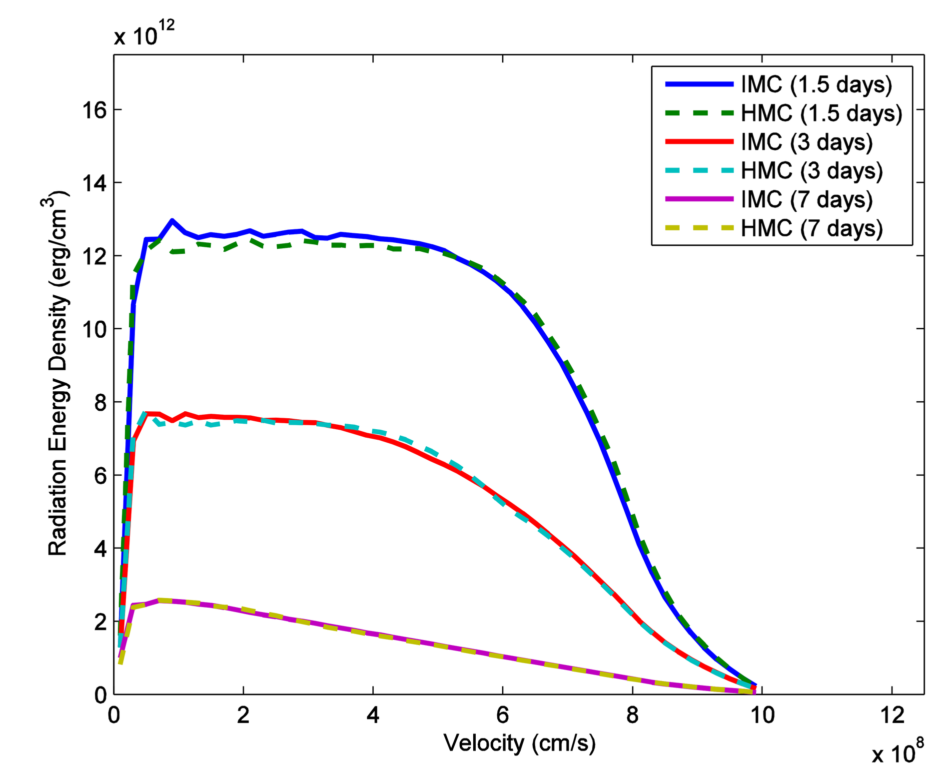

Figure 6: Radiation energy density for IMC (solid lines) and HMC (dashed lines) for 1e9 cm/s outflow and 1e7 disparity between opacities of adjacent groups. A three mfp threshold between IMC and DDMC makes HMC faster than IMC by factor of 4.59.