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A new approach to neutrino transport in 3D simulations of core-collapse supernovae

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We introduce the ELEPHANT code and present results from a preliminary 3D simulation of a core-collapse supernova which includes multi-group neutrino transport. Computational techniques used for neutrino transport in two dimensions are prohibitively expensive in 3D, and three dimensional effects such as convection and asymmetric accretion may play an important role in a supernova explosion. The multi-group treatment based on the isotropic diffusion source approximation allows for detailed input of microscopic physics in large-scale hydrodynamic simulations.

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1. Introduction

The mechanism which causes a core-collapse supernova to explode is presently not fully understood. Simulations can model the collapse and bounce phases, but the shock expansion stalls around a few hundred kilometres. The majority of the energy from a supernova is radiated away as neutrinos, and it has been suggested that some of these neutrinos heat the matter behind the stalled accretion shock and revive the explosion [1].

One dimensional hydrodynamic simulations with neutrino transport have been done for many years, and have given valuable insight into the problem [4]. However, phenomena such as convection are thought to play an important role in the explosion mechanism [2], and this can only be simulated properly in three dimensions. Three dimensional magnetohydrodynamic simulations with neutrino transport are extremely challenging to develop, however the recent development of the Isotropic Diffusion Source Approximation has enabled us to begin to perform three-dimensional simulations of core-collapse supernova with neutrino transport.

2. ELEPHANT and the Isotropic Diffusion Source Approximation

ELEPHANT (*Ele*gant *P*arallel *H*ydrodynamics with *A*pproximate *N*eutrino *T*ransport) is based on the simple and fast cosmological magnetohydrodynamics code of Pen, Arras and Wong ([7]). The code has been parallelised and adapted for use in supernova simulations [3]. It includes a sophisticated nuclear equation of state, and gravity is included using a spherically symmetric mass integration with general relativistic corrections [6]. The code has an equidistant Cartesian grid embedded inside a spherical domain which provides the boundary conditions.

ELEPHANT performs neutrino transport using the Isotropic Diffusion Source Approximation (IDSA; [5]). This is a sophisticated approximation for including neutrino transport in three dimensional simulations. The IDSA involves decomposing the distribution function into two components and using different computational methods to solve each component separately. The decomposition is based on whether the neutrinos are trapped in the local fluid element by the opacity, or whether they are free to stream through the fluid. The IDSA is computationally more expensive than hydrodynamics, as it solves for twelve different neutrino energies and two neutrino species. However it is possible to run simulations much faster than with Boltzmann neutrino transport.

3. Results

Figure 1 shows a comparison between a one-dimensional implementation of the IDSA (blue line) and the results of a spherically symmetric Boltzmann calculation (black line). There are two different times plotted in the figure, 30ms (leftmost pair of lines) and 100ms (rightmost pair) after core bounce. The agreement between the IDSA and a proper numerical solution of the Boltzmann equation is excellent. Other hydrodynamic quantities show a similar match with the Boltzmann solution.

Figure 2 demonstrates how closely a one-dimensional implementation of the IDSA (red line) matches the neutrino fraction given by a solution of the Boltzmann equation (blue line). As mentioned above, the IDSA decomposes the distribution function of the neutrinos into two different

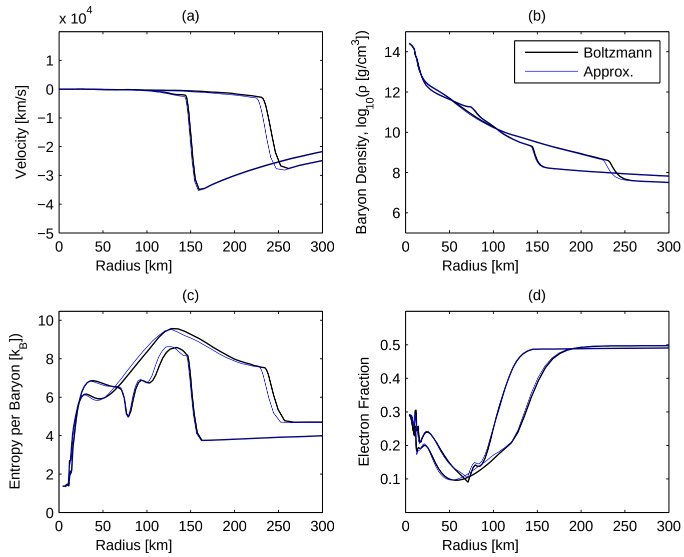

Figure 1: A comparison between the density, entropy, electron fraction and velocity profiles of a one-dimensional implementation of the isotropic diffusion source approximation (blue) and a spherically-symmetric Boltzmann calculation (black) with the same physics. The quantities are plotted at two different times, 30ms (leftmost lines) and 100ms (rightmost lines) after core bounce.

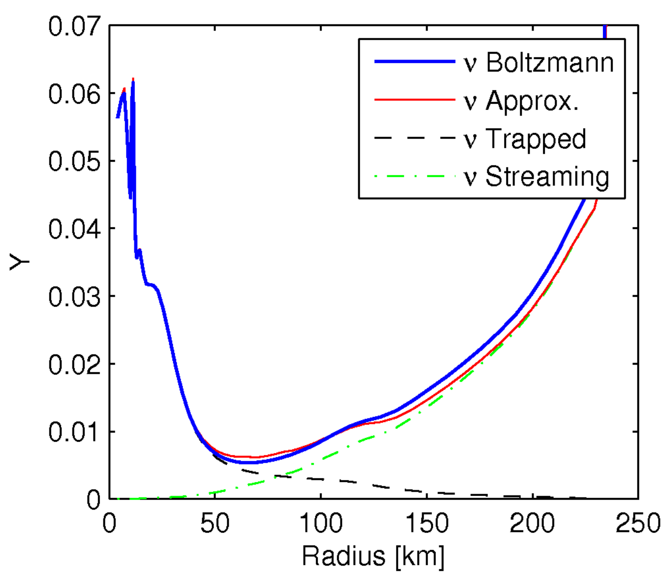

Figure 2: The neutrino fraction Y of the Boltzmann solution (blue line) and the IDSA (red line) . The decomposition of the IDSA into separate trapped and streaming particles can be seen as the dashed black line and the dot-dashed green line respectively - summing the black and green lines gives the red line.

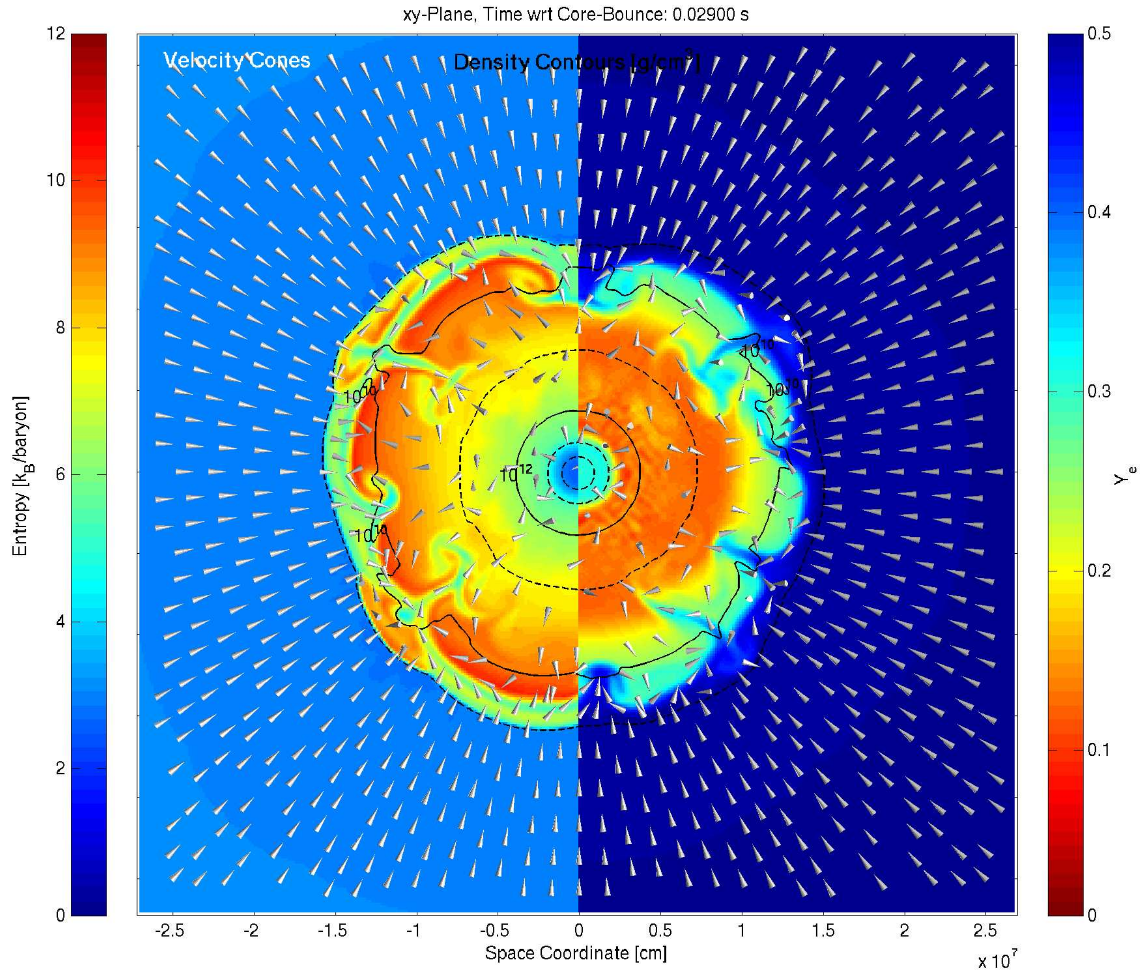

Figure 3: This shows a slice through the equatorial plane of a simulation including neutrino transport using the IDSA 29 ms after core bounce. The left-hand half of the figure shows the entropy, and the right-hand half shows the electron fraction. The white cones show show the fluid motion and the black lines are lines of constant density. The initial pre-collapse model was 15 solar masses, and had no initial rotation or magnetic field. The resolution of this simulation is 1.5 kilometres in all three Cartesian directions

components, which can be seen here as the black and green lines. Adding together the neutrino fractions shown by black and green lines gives the total neutrino fraction for the IDSA (red line). Close to the proto-neutron star most neutrinos are trapped, whereas in the outer layers the streaming component dominates. As the figure clearly shows, the result of the IDSA matches the solution of the Boltzmann equation very well.

Figure 3 shows a cross-section through the equatorial plane of a simulation using ELEPHANT. The figure shows the entropy on the left and the electron fraction on the right, together with the velocity field (white cones) and the density (black lines of constant density). The orange region in the right-hand part of the figure, near to the proto-neutron star, is the region of low electron fraction due to the neutronisation burst. Here the reaction rates are high, and the opacity is low, so the neutrinos stream out of the region. In the interior of the proto-neutron star the diffusion timescale is long, so few neutrinos are emitted keeping the electron fraction high. In the outer regions the reaction rates are low, so few neutrinos are produced. The accretion shock can be seen on the left where the low-entropy matter is falling onto the central region of high-entropy matter. This preliminary model is the first three-dimensional simulation of a core-collapse supernova which includes spectral neutrino transport.

4. Conclusions

The ELEPHANT code is capable of performing efficient neutrino transport in the context of three-dimensional magneto-hydrodynamical simulations of core-collapse supernovae. Using the innovative "isotropic diffusion source approximation" to perform neutrino transport in three dimensions enables simulations to be performed in a reasonable amount of computer time. This code will enable us to perform a detailed investigation into the physical processes and features which dominate in core-collapse supernovae.

Acknowledgments

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