Shaping neutrino transport for a portable DIAPHANE radiative transfer library

Platform for Advanced Scientific Computing

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Introduction

Neutrinos are among the least interacting particles in the universe. Nevertheless, they play a capital role in many astrophysical scenarios that involve compact objects, like Neutron Stars (NS) and Black Holes (BH), or very energetic explosions like Core Collapse Supernova (CCSN).

These highly dynamic, multi-scale and multi-physics scenarios pose a problem of enormous proportions, that can only be tackled by numerical simulations. In such simulations, neutrino transport represents the main bottleneck, because the different spatial and momentum directions of radiative transfer blow a three-dimensional problem up to six dimensions. That's why we have to rely on approximations to the full Boltzmann equation that still keep the dominant coupling between matter and the radiation field.

To that extent we have developed several neutrino treatment schemes and, within the framework of the DIAPHANE project, ported them to very different hydrodynamical codes. In this way, we set the ground to the development of a portable radiation library.

Computational tools

In the following table we list the hydrodynamical codes and neutrino treatment schemes that we dispose, and their status in terms of portability and production:

Hydrocode	Description	Neutrino treatment	Status
ELEPHANT	Eulerian Fixed Cartesian mesh (OpenMP+OpenACC+MPI)	IDSA	Production
		ASL	Ported
FLASH	Eulerian AMR Cartesian mesh (OpenACC+MPI)	IDSA	Production
SPHYNX	Lagrangian SPH (OpenMP+MPI)	IDSA	Ported
		ASL	Production

IDSA *(Isotropic Diffusion Source Approximation)* is an approximate spectral neutrino transport scheme with 3D diffusion for all electron neutrino species. It splits the neutrino distribution function in two components (trapped and streaming) coupling them via a source that is consistent with the diffusion limit. It is OpenMP/OpenACC parallelized.

ASL *(Advanced Spectral Leakage)* is an improved spectral leakage scheme for all neutrino species, that instead of solving diffusion evaluates the neutrino cooling rates by interpolating local production and diffusion rates. It also includes physically motivated non-local neutrino heating processes, and it is OpenMP parallelized.

References

B. Fryxell, et al. – **ApJS 131 (2000)**
D. García-Senz, R. M. Cabezón, J. Escartín – **A&A 538 (2012)**
R. Käppeli, et al. – **ApJS 195 (2011)**
M. Liebendörfer, S. C. Whitehouse, T. Fischer – **ApJ 698 (2009)**
P. MacNeice, et al. – **CPC 126 (2000)**
K.-C. Pan, M. Liebendörfer, M. Hempel, F.-K. Thielemann – **arXiv:1505.02513**
A. Perego, R.M. Cabezón, R. Käppeli – **arXiv:1511.08519**

Porting Neutrino Transport

Both ELEPHANT and FLASH are 3D grid-based Eulerian hydrodynamics codes. ELEPHANT has an equidistant Cartesian mesh. FLASH-IDSA uses the block-structured oct-tree based Adaptive Mesh Refinement (AMR) with the PARAMESH4 library. Therefore, to port IDSA for the neutrino transport, the hydrodynamic solver includes additional equations that advect the trapped electron neutrino and anti-neutrino fractions (Y_ν^t) and a multiple of the neutrino entropies, $(\rho Z_\nu^t)^{\frac{3}{4}}$, where Z_ν^t is the mean neutrino energy. Then, the evolution of the trapped neutrino sources is provided by IDSA.

SPHYNX is a 3D particle-based Lagrangian SPH code. In this case the porting required a change of focus, as we were dealing with particles and not with cells. Fortunately, IDSA and ASL are describing mostly local processes that can be easily applied to the Lagrangian point of view of SPH. The philosophy was to adapt the schemes as independently from the hydrodynamics as possible. The neutrino scheme is applied to each particle in combination with an SPH 3D explicit diffusion solver and an evolution equation for Z_ν (energy stored in the trapped neutrino field). The latter is implemented in a semi-implicit way:

$$Z_{\nu,i}^{n+1} = \frac{Z_{\nu,i}^{n} + \frac{dZ_{\nu,i}^{n}}{dt}\Delta t}{1 - \frac{1}{3\Omega_i \rho_i}\sum_j m_j \left(\mathrm{v}_i - \mathrm{v}_j\right)\mathcal{A}_{ij}\Delta t}$$

Where, Ω_i are the grad-h terms and $\mathcal{A}_{ij}$ are the Integral Approach to Derivatives (IAD) terms.

Results

Our algorithms have been validated and calibrated for the simulation of core collapse supernovae and are now moving to production. These first successful ports have revealed common structures in the algorithms and lead to more universal modules from which the DIAPHANE library will benefit.

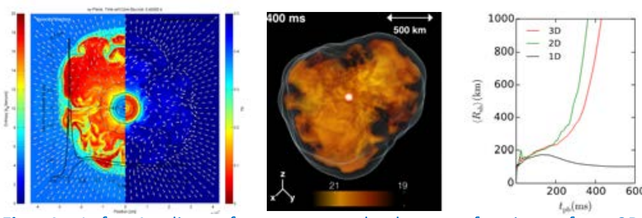

Fig. 1: Left: A slice of entropy and electron fraction of a 3D ELEPHANT+IDSA CCSN simulation of a 15M$_\odot$ progenitor. Central: 3D volume rendering of entropy for a CCSN with FLASH+IDSA at 400 ms postbounce. The supernova shock is visible by the thin surrounding silver line. Right: A comparison of averaged shock radius of FLASH+IDSA simulations with different spatial dimensions.

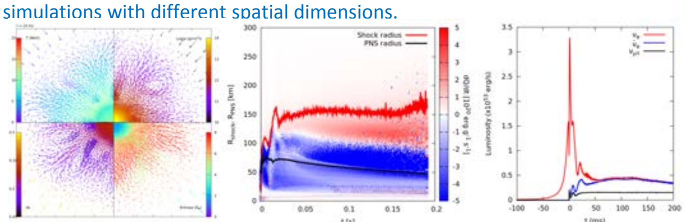

Fig. 2: Left: slice at 10 ms postbounce for the 3D CCSN in SPH+ASL of a 15M$_\odot$ progenitor. Each arrow represents one SPH particle and shows its projected velocity. Temperature, density, Ye, and entropy are color coded. Central: evolution of the PNS and shock radius. Color coded is the net energy deposition by electron neutrinos. Right: Temporal evolution of the neutrino luminosities.

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