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DIAPHANE: A portable radiation transport library for astrophysical applications

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ABSTRACT

One of the most computationally demanding aspects of the hydrodynamical modeling of Astrophysical phenomena is the transport of energy by radiation or relativistic particles. Physical processes involving energy transport are ubiquitous and of capital importance in many scenarios ranging from planet formation to cosmic structure evolution, including explosive events like core collapse supernova or gamma-ray bursts. Moreover, the ability to model and hence understand these processes has often been limited by the approximations and incompleteness in the treatment of radiation and relativistic particles. The DIAPHANE project has focused on developing a portable and scalable library that handles the transport of radiation and particles (in particular neutrinos) independently of the underlying hydrodynamic code. In this work, we present the computational framework and the functionalities of the first version of the DIAPHANE library, which has been successfully ported to three different smoothed-particle hydrodynamic codes, GADGET2, GASOLINE and SPHYNX. We also present validation of different modules solving the equations of radiation and neutrino transport using different numerical schemes.

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1. Introduction

The goal of the DIAPHANE library is to enable advances in computational modeling of complex astrophysical processes in which the transfer of energy by radiation or neutrinos is important. DIAPHANE has been supported by the PASC[1] initiative, which aims to promote the development of software that can fully utilize new and emerging supercomputing hardware technology. Astrophysics simulations are currently able to capture many of the most relevant hydrodynamical and gravitational processes involved in the formation and evolution of stars, planets, and galaxies. However, our advancement has been limited in a number of physical situations where energy transport by radiation or neutrinos is important. This project aims to improve the situation by providing a library of radiation and neutrino transport routines covering a range of physical regimes relevant for a wide range of astrophysics simulations, and also able to be used simultaneously within a single simulation. We hope that the modular and extensible nature of this library will facilitate community contributions in the form of additional physics routines and other improvements after its initial public release.

There are two primary reasons that including radiation and neutrino transport (RT/NT) in astrophysical simulations has been limited in scope. (1) The characteristic timescale for radiative and neutrino processes is very short compared to that of hydrodynamic processes. This is because the speed of light is much faster than the sound speed—light travels $\sim 10^4$ times faster than sound in the molecular clouds where stars are forming. This means that simulation timesteps must be very short in order to accurately model the problem, increasing the global computation time, in some cases, to scales that are unaffordable nowadays. And (2), RT/NT modeling is complex due to the many different processes involved at the atomic scale (e.g. emission, absorption, scattering). This complexity is increased by the fact that a vast majority of astrophysical scenarios are intrinsically three-dimensional (3D), which translates into solving a full Boltzmann transport equation in 6D. This situation raises 3D hydrodynamical simulations with full RT/NT modeling to problems that lie well within the sustained Exascale.

To skirt the computational complexity, RT/NT codes must implement approximate algorithms. Typically, approximated RT/NT algorithms work well only for a specific range of conditions, e.g. optically thin diffuse gas with a single radiative source. Nevertheless,

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[1] http://www.pasc-ch.org/.

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most astrophysical phenomena include a large dynamic range and a corresponding large effective range in optical depth, so are not suited to be modeled by a single RT/NT approximate algorithm. The DIAPHANE project is unique at the moment in the international astrophysics community as it gathers different RT/NT approximations under a common portable framework, while so far, individual hydro codes have used only one or two radiative transfer solvers tailored to very specific problems, in very specific regimes, and adapted to very specific hydrodynamics implementation.

As a consequence, our understanding of the complex astrophysical Universe is hindered by the lack of radiation and neutrino transport (RT/NT) in our computational modeling of star and galaxy formation; planet formation; supernova explosions; and black hole formation. We note that both the short timescales and the complex physics algorithms are very similar for RT and NT; for this reason it is effective and convenient to model the transport of radiation and neutrinos within a single framework implemented as a single library.

Radiation transport is important for the dynamics of many astrophysical processes. Radiative feedback from stars and black holes plays a dominant role in regulating the rate of gas accretion into galaxies and star formation within galaxies. The accumulated regulation of star formation determines the observable galaxy properties such as stellar luminosity, color, and age. Because radiation can couple across a range of scales and conditions, multiple modes of RT modeling capabilities allow us to solve new classes of problems. For example, a planet-forming disk around a protostar requires modeling the star light from the protostar as well as diffusion of that radiation outward through the planet forming disk. Evolving the disk temperature accurately, in this case, is needed to follow the fragmentation of the disk which ultimately determines the number and masses of planets that form.

Neutrino transport is of capital importance for understanding the explosion mechanism of one of the most powerful events in the Universe: core collapse supernovas. During the last phases of the lives of massive stars ($M > 8{-}10 M_{sun}$), a fast collapse of the core drives the formation of a neutron star via a strong deleptonization. As a result, an incredibly large quantity of neutrinos of all species is emitted. The interaction of these neutrinos, produced by the newly born neutron star, with the ensuing shockwave is critical to adequately understanding how the energy reservoir is tapped to energize and produce the explosions that we observe. Additionally, in the later phases of the explosion, as well as in different scenarios like neutron star mergers, the emission of highly neutronized matter by neutrino-driven winds is very important for characterizing the contribution of these scenarios to the r-process elements and understanding the origin of the nuclear abundances observed in the Galaxy. Therefore, the correct simulation of the neutrino–matter interactions in 3D geometrically distorted scenarios is the cornerstone of our understanding to such fundamental questions.

2. The *DIAPHANE* library

2.1. Overview of library modules for RT/NT physical processes

Common Utilities: This module handles many fundamental operations, ranging from defining the data structure to calculating quantities such as the opacity or the optical depth of gas given its physical conditions; these can be used by other library modules or called directly from a hydro simulation code as needed.

Flux-Limited Diffusion (FLD): This is a relatively simple yet powerful method to approximate radiative diffusion. For this reason, FLD served as our 'prototype' module and was the first module to be ported to the library and validated for each of the three hydrodynamical codes included in the project. FLD is treated as thermal conduction as in [1,2]. Therein, photons diffuse in the direction of the local energy gradient. FLD is most accurate when gas is optically thick, typical of dense star-forming or planet-forming gas. In this regime, the FLD energy transport rate matches the diffusion limit, governed by the random walk of photon scattering. See Section 2.3.1 for more details.

Starrad: This newly developed ray casting method tracks the direct propagation of energy from a heating source, such as a star, to the surrounding medium, by casting rays onto a spherical angular grid and numerically solving the radiative transfer equation considering the absorption of the medium along each ray. STARRAD is a new type of algorithm in the context of particle based codes. This technique of grid-based ray-tracing has been only used in grid-based codes to our knowledge (e.g. FLASH, ENZO). See Section 2.3.2 for more details.

Advanced Spectral Leakage (ASL) [3]: This is a novel approximate neutrino treatment that computes the neutrino cooling rates by interpolating local production and diffusion rates (relevant in optically thin and thick regimes, respectively) separately for discretized values of the neutrino energy. Neutrino trapped components are also modeled, based on equilibrium and timescale arguments. The better accuracy achieved by the spectral treatment allows a more reliable computation of neutrino heating rates in optically thin conditions. See Section 2.3.3 for more details.

Isotropic Diffusion Source Approximation (IDSA) [4]: IDSA is a more sophisticated scheme in which the distribution function of the neutrinos is decomposed into two components: trapped and streaming. Their separate evolution equations are coupled by a source term that converts trapped particles into streaming particles. The efficiency of the scheme, when compared with a more detailed solution of the Boltzmann equation, results from the freedom to use different approximations for each particle component.

TRAPHIC (TRAnsport PHotons In Cones) [5]: TRAPHIC is designed to model radiation from multiple sources efficiently. An example problem is to model the heating and ionization of gas in the inter-galactic medium during the stage of rapidly increasing galaxy formation in the first billion years of the Universe. The TRAPHIC module has been ported and used in post-processing mode between GADGET3 and GASOLINE in recent work on galaxy formation within our collaboration; see [6].

2.2. Implementation details

In the following we outline some details of the DIAPHANE library implementation.

2.2.1. Library

The library is currently hosted in a Bitbucket repository. The attached link[2] points to the repository wiki, and will also contain the public release of DIAPHANE in 2018 following a trial of validation and production runs conducted within the collaboration; v1.0 will consist of the first three modules (FLD, STARRAD, ASL) along with full documentation. The code will be published in the Computer Physics Communications (CPC) program library upon initial release.

The developmental focal points of the library are:

- *modular*: Because there are a multitude of RT/NT algorithms and approximations, each having advantages or disadvantages in terms of accuracy and efficiency for specific physical conditions, it is convenient to design DIAPHANE with a modular structure, so that adding new functionality is reasonably easy.

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[2] https://bitbucket.org/diaphane/diaphane-library.

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