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TREVR: A general $N \log^2 N$ radiative transfer algorithm

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ABSTRACT
We present TREVR (Tree-based REVerse Ray Tracing), a general algorithm for computing the radiation field, including absorption, in astrophysical simulations. TREVR is designed to handle large numbers of sources and absorbers; it is based on a tree data structure and is thus suited to codes that use trees for their gravity or hydrodynamics solvers (e.g. Adaptive Mesh Refinement). It achieves computational speed while maintaining a specified accuracy via controlled lowering of the resolution of both sources and rays from each source. TREVR computes the radiation field in order $N \log N_{\rm source}$ time without absorption and order $N \log N_{\rm source} \log N$ time with absorption. These scalings arise from merging sources of radiation according to an opening angle criterion and walking the tree structure to trace a ray to a depth that gives the chosen accuracy for absorption. The absorption-depth refinement criterion is unique to TREVR. We provide a suite of tests demonstrating the algorithm's ability to accurately compute fluxes, ionization fronts and shadows.

Key words: radiative transfer – methods: numerical

1 INTRODUCTION

Radiation, arguably, plays the determining role in the field of astrophysics. Almost all of the information we receive from the cosmos comes in the form of photons we detect on or around earth. Understanding the process of radiative transfer (RT) is required to interpret this information, as the photons are affected by the media they travel through on their way to our telescopes and detectors. Interactions between photons and these media not only affect the photons themselves but the matter as well. Photons and baryons exchange energy and momentum, driving both heating and cooling. This also affects excitation and ionization states and thus determines the chemical and thermodynamic properties of the gas. Thus radiation is a key player in many of the astrophysical systems and processes we study.

On galaxy scales, a central question is how feedback mechanisms affect star and galaxy formation. Stellar feedback comes in the form of photoionization by ultraviolet (UV) radiation, stellar winds and supernovae (e.g. Leitherer et al. 1999), the latter of which has been a main focus in simulations in previous years (e.g. Agertz et al. 2013). It is important to note that even though supernovae might be spectacularly powerful events, ionizing radiative output from stellar populations contributes two orders of magnitude more energy at early times and about 50 times more energy over the course of a stellar population's lifetime. This is evident from Figure 1, which is a plot of the luminosity output per solar mass as a function of time from a typical stellar population (computed using the stellar evolution code Starburst99; Leitherer et al. 1999).

However, the way in which this massive output of UV radiation is deposited and consequently affects the interstellar medium (ISM) is still unclear. Attempts at numerically exploring these effects without the use of a full radiative transfer method have produced conflicting results. Simulations done by Gritschneder et al. (2009) and Walch et al. (2012) suggest that ionizing feed back from large O-type stars before the first supernovae ($\sim 1-3$Myr) have a significant effect on star formation rate. Whereas Dale et al. (2012) conclude the effects on star formation rate to be small.

With this potential impact in mind, it may seem surprising that RT has been treated poorly in most galaxy-scale astrophysical simulations, often as an imposed uniform background. This is because RT is an intrinsically complex and computationally expensive problem. The complexity is immediately evident from the full RT equation (e.g. Mihalas & Mihalas 1984),

$$\left[\frac{1}{c}\frac{\partial}{\partial t} + \mathbf{n}\cdot\nabla\right] I\left(\mathbf{x},\mathbf{n},t,\nu\right) = \epsilon\left(\mathbf{x},\mathbf{n},t,\nu\right) - \alpha\left(\mathbf{x},\mathbf{n},t,\nu\right) I\left(\mathbf{x},\mathbf{n},t,\nu\right). \quad (1)$$

Here, I, ϵ and α are the intensity, emissivity and extinction coefficients respectively and all depend on position $\mathbf{x}$, unit direction of light propagation $\mathbf{n}$, time t and frequency

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