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MODELING PERIODIC MEDIA WITH THE THREE-DIMENSIONAL RADIATIVE TRANSFER CODE IRIS

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Abstract. We describe the implementation in our generic three-dimensional radiative transfer code, IRIS, of an algorithm that allows the modeling of periodic infinite media. We show how this algorithm has been validated by comparison with well-established 1D plane-parallel models. A particularly interesting astrophysical application will be the calculation of synthetic spectra of the fully three-dimensional solar atmosphere.

Keywords: methods: numerical, radiative transfer

1 Introduction

Radiation is a major component of many astrophysical objects, as a probe of the physical state of the medium, but also as a contributor to the momentum and energy budget of the medium. An accurate modeling of the radiative transfer is, therefore, a key element for the determination of the composition and the physical properties of such objects. To this end, we have developed a generic 3D radiative transfer code, IRIS, that post-processes radiation magnetohydrodynamics simulations, in order to provide spectroscopic signatures.

Although the code can be applied to a wide range of astrophysical objects, we focus here on the specific case of infinite media with double periodicity in one plane. This is typically the case for the solar atmosphere, for which the code will be able to provide synthetic spectra from hydrodynamic simulations, and for cosmological simulations.

The main characteristics of IRIS are summarized in § 2. In § 3, we explain the method of taking into account the periodic boundary conditions. We show how our approach has been validated through comparison with results obtained with a specific horizontally periodic medium: the 1D plane-parallel medium.

2 Overview of IRIS code

IRIS is a new generic three-dimensional radiative transfer code (Ibgui et al. 2011, 2012). Its purpose is to post-process 3D (radiation) (magneto)hydrodynamics (RMHD) simulations, in order to provide spectroscopic signatures of a given astrophysical object. It solves the exact monochromatic 3D static radiative transfer equation (RTE), in a Cartesian grid that is nonuniform in each direction. The thermodynamic properties (temperature, density, velocity) are determined from the RMHD simulations. We assume local thermodynamic equilibrium (LTE). This restriction will be removed in the future. The opacities are defined at each grid point for a grid of frequencies. The specific intensity is calculated for all the frequencies at each grid point, with the short-characteristics method (Kunasz & Auer 1988). The latter is coupled with an efficient interpolation technique that uses piecewise cubic, locally monotonic, polynomials. Such interpolants drastically restrain the known numerical diffusion effect of the short-characteristics method. The code determines the following quantities, which are functions of the frequency ν and the position (x, y, z): the mean intensity J, the three components of the radiation flux vector F_x, F_y, F_z, the six components of the radiation pressure tensor P_{xx}, P_{yy}, P_{zz}, P_{xy}, P_{xz}, P_{yz}. Many more details are provided in the paper by Ibgui et al. (2012). The user can fully specify the boundary conditions for a well-delimited medium. This is not possible in the case of a horizontally periodic infinite medium as we explain below.

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3 Boundary Conditions for Horizontally Periodic Media

3.1 Method

We consider a three-dimensional medium with an infinite extension in the horizontal plane (x, y), and a finite extension along the vertical z-axis between its lower boundary $z_{\rm min}$ and its upper boundary $z_{\rm max}$. We assume that this medium has a double periodicity, one in x-direction, one in y-direction. Boundary conditions are known at $z_{\rm min}$ and $z_{\rm max}$. For example, we may consider a non-irradiated stellar atmosphere with no incoming radiation at the outer surface $z_{\rm max}$ and a black body radiation at its inner surface $z_{\rm min}$. The computational grid ranges from $z_{\rm min}$ to $z_{\rm max}$ in vertical direction, from $x_{\rm min}$ to $x_{\rm max}$, and from $y_{\rm min}$ to $y_{\rm max}$ in the horizontal plane, so that $(x_{\rm max} - x_{\rm min})$ defines a period in x-direction and $(y_{\rm max} - y_{\rm min})$ defines a period in y-direction. Now, we remind that the short-characteristics method consists in solving the integral form of RTE by propagating the rays from one upwind boundary in which the specific intensity is known, throughout the computational domain, down to the downwind boundary. For periodic media, while the vertical boundary conditions are explicitly defined (see above), the lateral boundary conditions are implicitly defined, such as, for any physical quantity $f(\nu, x, y, z)$ we have the following relations:

$$f(\nu, x_{\rm max}, y, z) = f(\nu, x_{\rm min}, y, z), \qquad \text{for any } y, z, \tag{3.1}$$

$$f(\nu, x, y_{\rm max}, z) = f(\nu, x, y_{\rm min}, z), \qquad \text{for any } x, z. \tag{3.2}$$

Consequently, when the upwind edge of a short-characteristic intersects a lateral boundary (see Fig. 1), we prolong this characteristic, which becomes a long-characteristic, until it intersects a horizontal face, following the suggestions by Auer et al. (1994) and Fabiani Bendicho (2003). For a given direction of propagation, and for each z-layer, this treatment affects only the cells in the first x-row and first y-row, i.e., the boundary rows. Since the medium is horizontally periodic, we can start the propagation of the rays at any x-row and any y-row, provided that we span the whole period in x and the whole period in y. In order to minimize the number of cells that are intersected by the long-characteristics, which saves cpu time, we define our first x-row as the one for which the corresponding cell size Δx is the largest, and, in the same vein, our first y-row as the one for which Δy is the largest. Once these two rows have been treated, we resume the short-characteristics method for the next rows of the current z-layer.

3.2 Comparison with 1D plane-parallel models

This method has been tested by comparison with the results provided by well-tested 1D methods in the case of a 1D plane-parallel medium. The test case is a simulation of an experimental radiative shock, generated in a tube full of Xenon, assumed to be a perfect gas, with the following upstream conditions: fluid velocity = 60 km s^{-1}, pressure = 7 bar, temperature = 1 eV. The hydrodynamics results are provided by Matthias González[i] with the code HERACLES (González et al. 2007). The opacities are from Michaut et al. (2004). Figure 2 shows results provided by IRIS, in comparison with the results from a 1D solver. By way of example, we show, at the frequency $h\nu = 296$ eV ($h\nu = 4.19\ nm$), the radiation flux in z-direction, $F_z(z)$, and the components $P_{zz}(z)$, $P_{xx}(z)$, and $P_{yy}(z)$ of the radiation pressure tensor. The results obtained by IRIS and by the 1D code perfectly match. In addition, IRIS verifies the following properties of a 1D plane-parallel medium, valid for any frequency: F_z does not depend on x and y, $F_x = F_y = 0$, $P_{xy} = P_{xz} = P_{yz} = 0$, and $P_{xx} = P_{yy}$ for any (x, y, z). Above all, we have validated the calculation of the specific intensity for all the 8 octants and verified that I is independent of the azimuthal angle φ.

4 Conclusion

The three-dimensional radiative transfer code, IRIS, which solves the monochromatic 3D radiative transfer equation, can take into account any medium with a horizontal periodicity. Obtaining synthetic spectra from 3D hydrodynamic simulations of the solar atmosphere, as well as for cosmological simulations, is one of our primary objectives.

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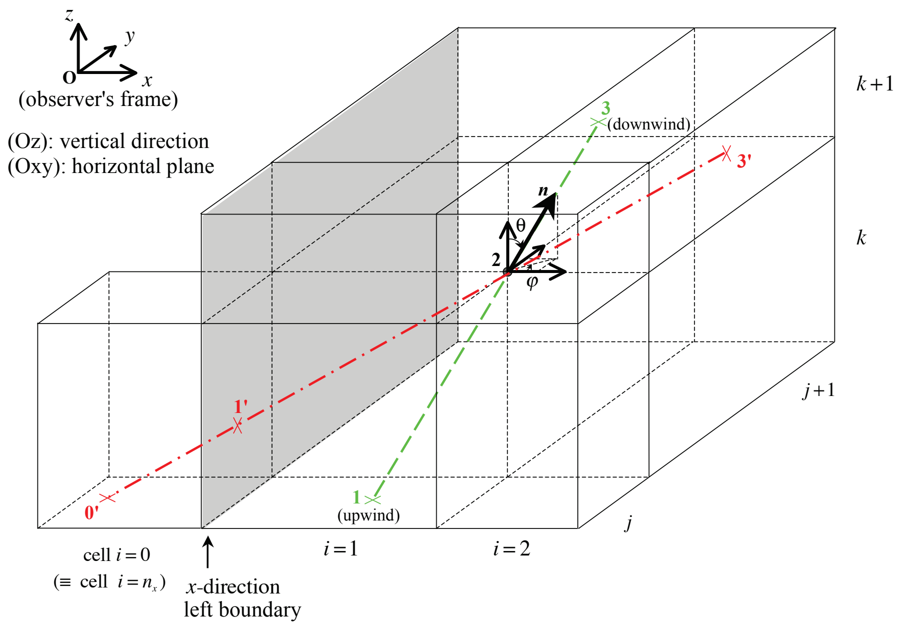
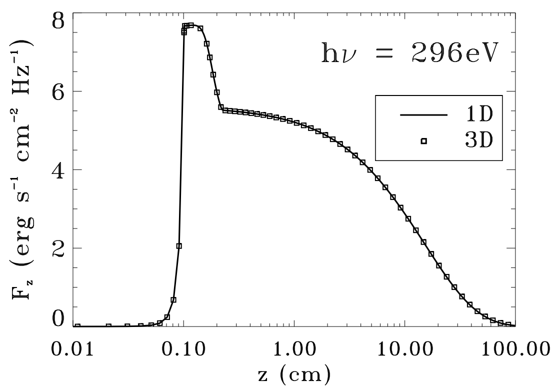


Fig. 1. Horizontally periodic medium. The upwind specific intensity is known at point 1 (that lies on a horizontal face) for the short-characteristic (1,2,3). The upwind specific intensity is not known at point 1' (lateral boundary of the grid) for the short-characteristic (1',2,3'). The latter is therefore prolonged until it intersects a horizontal face.



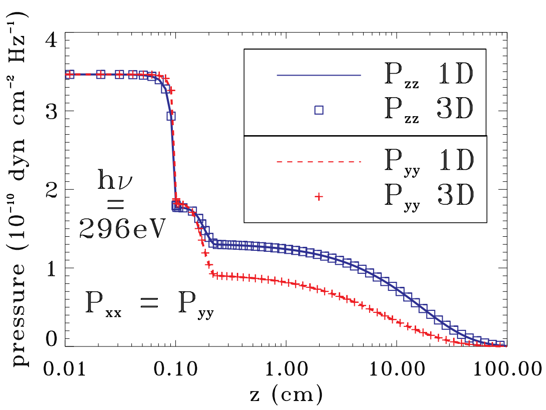


Fig. 2. Results from IRIS with periodic boundary conditions, and from a 1D solver, for a 1D plane-parallel medium, at $h\nu = 296$ eV. **Left:** radiation flux $F_z(z)$, **Right:** radiation pressure $P_{zz}(z)$, $P_{xx}(z) = P_{yy}(z)$.

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