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Applying Monte Carlo methods to model multi-wavelength emission of RMHD jet simulations.

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Relativistic jets associated with active galactic nuclei (AGN) produce radiation over a large range of the electromagnetic spectrum. While relativistic magneto-hydrodynamic (RMHD) simulations have become a powerful tool to model the physical structure of jets, in order to correlate them to observations, estimates of the radiation must also be determined. We present the initial results from a study to calculate the multi-wavelength radiation by applying Monte-Carlo methods, using the parameters provided by the RMHD simulations. We present our initial implementation of a Monte Carlo code that interfaces with the RMHD simulation of a steady state axis-symmetric jet created using the PLUTO code. Properties such as the number density, energy density, magnetic field and bulk Lorentz factor are obtained from the RMHD simulations and used to generate a synchrotron photon distribution in each cell. These photons are tracked as they move through the simulation environment and undergoes inverse Compton scattering. Each photon is recorded when it exits the simulation domain and is used to construct multi-wavelength SEDs and light curves. This will provide a time-dependent, multi-zone Synchrotron Self-Compton (SSC) emission model for RMHD simulations.

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1. Introduction

The radiation observed from radio load AGN jets are dominated by non-thermal emission consisting of a broad low-frequency component produced by synchrotron radiation and a high-frequency component, which has been modelled with both leptonic and hadronic processes (see e.g. [1]). In the leptonic models the radiation is produced by inverse Compton scattering of electron/positrons from either photons produced externally to the jet or from the synchrotron photons produced in the jet (see e.g. [2, 3]).

These jets have complex dynamics which lead to variability in their emission over both intra day and long-term time scales (see e.g. [4]). The blazar class of AGN, in which the relativistic jet is orientated towards the line of sight of the observer, are particularly known for their high short term variability and flares. Observations of variability show that outbursts can have many different profiles and studies have found both correlations and anti-correlations between variability in different wavelength regimes. This range of properties in the observed variability is likely produced by the combination of multiple physical processes from the central engine as well as the jet. To better understand the dynamics and physical environments in AGN jets, many studies have been undertaken using numerical RMHD simulations ([5, 6]). While RMHD simulations provide a tool to investigate structures such as shock fronts, sheath layers and the magnetic field orientation inside a jet, in order to relate the plasma properties modelled in these simulations to the observed non-thermal emission, additional radiative transfer mechanisms must be incorporated into the simulations.

Several methods have been developed to calculate the emission that would be produced by hydrodynamic simulation (see e.g. [7, 8]). Most of these methods, however, focus only on the synchrotron spectrum, while few incorporate external Compton models. One challenge that remains is the modelling of the synchrotron self Compton spectrum (SSC). To model the SSC spectrum of these simulations, the synchrotron spectrum produced by all of the surrounding cells must first be known. Along with this, effects such as Doppler boosting and light travel time becomes vital due to the large distance scales spanned by these sources.

Monte Carlo (MC) models have previously been used to create multi-zone stationary models of the spectral energy distribution (SED) for AGN. Chen et al. 2011 [9] showed that these MC methods can be extended to time dependent models. In these methods MC photons are generated and tracked in a domain. The photons are sampled from an initial spectrum for each zone and all subsequent absorption and scattering processes occur with regards to the MC photons. This reduces the computational costs of the simulation since the full integration of emission for each zone is not required. The position of the MC photons are tracked at each time step of the simulation, which inherently incorporates the light travel time effects.

In this contribution we present our initial implementation of MC methods to model the SSC spectrum of RMHD simulations. By incorporating the MC models into RMHD simulations one can simulate the time dependent SSC for different processes and relate them to observational studies.

2. Numerical setup

For the initial implementation of MC methods in RMHD simulations a test simulation was constructed using the open source code PLUTO (ver 4.3, [10]). A 2.5D Axis symmetric domain

Bulk Lorentz factor	26
Density ratio	10^{-3}
Jet density (g.cm$^-$3)	10^{-24}
Mach number	10
Magnetization parameter (β_m)	0.15
Magnetic field (G)	0.15

Table 1: Jet injection parameters.

was constructed with a size of 200 x 500 cells. A background rest medium was assigned to the grid with uniform density and pressure. Jet material was injected through a nozzle with a radius of 10 cells defined on the the $z = 0$ boundary. A toroidal magnetic field was set up at the nozzle with a profile given by,

$$B_\phi = \begin{Bmatrix} B_m \frac{r}{r_m} \ if \ r < r_m, \\ B_m \frac{r_m}{r} \ if \ r > r_m, \\ 0 \quad if \ \ r > r_b \end{Bmatrix}, \tag{2.1}$$

where B_ϕ is the azimuth component of the magnetic field, B_m is the magnetic field strength at the magnetization radius r_m and r_b is the beam radius. The averaged magnetic field strength over the beam cross-section was chosen as 0.15 G. This resulted in a magnetization parameter $\beta_m = 0.15$, where

$$\beta = \frac{p_m}{p}, \tag{2.2}$$

in which p represents the thermal pressure and,

$$p_m = \frac{B^2}{8\pi}, \tag{2.3}$$

the magnetic pressure. A pressure matched model between the jet and ambient medium was used in order to collimate the injected material. Table 1 lists the parameters that were chosen for the jet injection. Our choice of parameters was based on the one zone test model shown in [9]. The environment was evolved with time using a linear interpolation method, third order Runga-Kutta time stepping and the HLLD Riemann solver [11].

3. Monte-Carlo emission modelling code

To model the SSC spectrum from the simulation we adapted the MC code previously used by [9]. The code produces MC photon particles at a random time with a random position and direction of motion. Each MC photon particle represents a group of photons with an energy and weight. The photons distribution is scaled based on the synchrotron spectrum for a single particle average over an isotropic pitch angle, given by,

$$P(\nu,\gamma) = \frac{3\sqrt{3}}{\pi}\frac{\sigma_T c U_B}{\nu_B} y^2 [K_{4/3}(y)K_{1/3}(y) - \frac{3}{5}](K^2_{4/3}(y) - K^2_{1/3}(y)), \tag{3.1}$$

where σ_T is the Thompson cross-section, c is the speed of light, U_B is the magnetic energy density,γ is the Lorentz factor of the electrons, ν_B is given by,

$$\nu_B = \frac{eB}{2\pi m_e c} \tag{3.2}$$

with e the charge of an electron and m_e is the electron rest mass. $K_x(y)$ is a modified Bessel function of order x, with

$$y = \frac{\nu}{3\gamma^2 \nu_B} \tag{3.3}$$

The photons position is evolved for a time step and it has a probability of undergoing IC scattering based on the value and limit of the Compton cross-section. Absorption processes are incorporated into the code through a reduction in the photon packet weight. When a photon reaches the outer boundary its position, direction, energy and weight are recorded.

The MC code was modified to take the energy density, number density, magnetic field and cell velocity provided by the hydrodynamical simulations as input. Additional modifications were made to the code to include the relativistic effects when a particle crosses between different cells. The time and position of the MC particle was defined in a stationary galactic frame while all other photon variables are defined in the co-moving frame of the cell. Lorentz transformations were included to transform the direction of motion, photon energy and weight between cell boundaries. This is necessary when considering RMHD simulations containing cells with different velocities.

The MC code is implemented during post-processing of the RMHD simulation. For the simulation we assumed each cell contained an electron spectrum consisting of both a thermal and non-thermal component. Our non-thermal component consisted of a single power law given by

$$n(\gamma) = n_0 \gamma^{-p} \tag{3.4}$$

where $n(\gamma)$ is the electron number density per energy, p is the spectral index and n_0 is a normalization constant. For our initial spectrum we chose $p = 2$, $\gamma_{min} = 1$ and $\gamma_{max} = 10^5$. The normalization constant was scaled per cell using a tracer injected with the jet material. This is based on the assumption that the injected jet material contains a large non-thermal population of electrons, while the ambient medium contains only a thermal population.

4. Results

The RMHD simulation was evolved for a time of 3×10^3 years. Figure 1 displays the density, pressure and velocity distributions. The results show the formation of a collimated relativistic beam surrounded by a cocoon region. The beam of the jet contains recollimation shocks which are most prominent close to the injection point. A thin sheath layer containing matter of higher density and lower bulk velocity separates the beam from the surrounding cocoon.

For the initial implementation of the MC code we selected a 16×16 cell region surrounding a recollimation shock in the beam. 10^5 MC particles were created and evolved for 100 time steps. All photons that were recorded propagating in the forward direction were binned together to create an SED. The photons were placed in energy bins based on their frequency. The resulting SED is shown in figure 2.

The SED shows the characteristic double peaked shape with the lower energy component peaking at 10^{15} Hz and the higher energy component at 10^{24} Hz. The synchrotron peak frequency obtained corresponds to the Intermediate BL Lac (IBL) class of AGN, however the peak power of 10^{57} erg.s^{-1} is much greater than that shown by observational data [12]. This may be caused by the combination of a high kinetic luminosity of 10^{46} erg.s^{-1}, which is more consistent to that of an FSRQ, and the absence of spectral evolution such as radiative cooling.

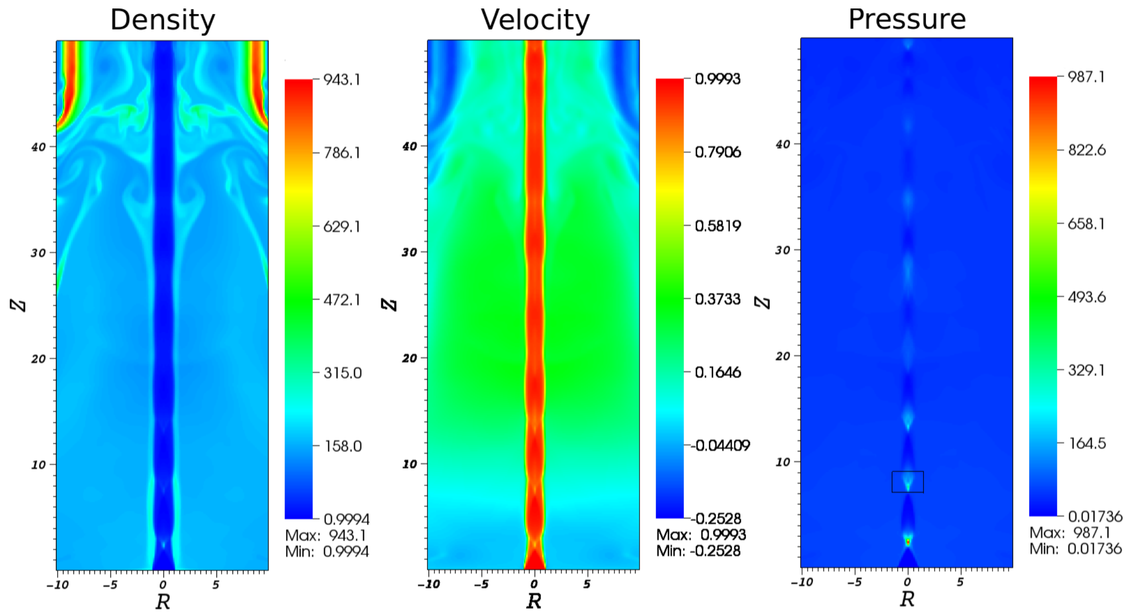

Figure 1: Figure 1: Density, velocity and pressure distributions of the RMHD simulation. The density and pressure are given in arbitrary units, while the velocity plots have a linear scaling in units of c. The box in the pressure distribution illustrates the region used for MC simulations.

5. Conclusion

A 2.5D numerical simulation of a collimated relativistic jet beam was created and evolved with time using the PLUTO code. MC methods were used to compute the spectral energy diagram for a 16×16 cell region of the beam. The resulting SED is consistent with that of an Intermediate peaked BL Lac with synchrotron frequency peak at 10^{15} Hz, however the power is much higher than that observed for IBL sources. This may be due to the use of a constant electron spectrum, neglecting effects such as radiative cooling. The shape and energy bins in the presented SED will be futher improved upon in future by increasing the the MC particle number and the evolution time. We are also currently incorporating temporal evolution of the electron spectrum through the Fokker-Planck equations used in previous versions of the MC code. In addition to this the hybrid particle module available in the latest version of PLUTO can be employed to better constrain the initial electron spectrum obtained from the hydrodynamic simulations.

The results presented are a good initial test of the modifications made to the MC code and the integration with PLUTO. By developing this method to model the SSC spectrum of RMHD simulations we will be able to better investigate the relationship between the dynamical structures obtained through simulations to that of observed data. Since the relevant time information of the MC photons are recorded when the particles escape the domain, we can also apply this technique to model the variability that would be observed im the RMHD simulations.

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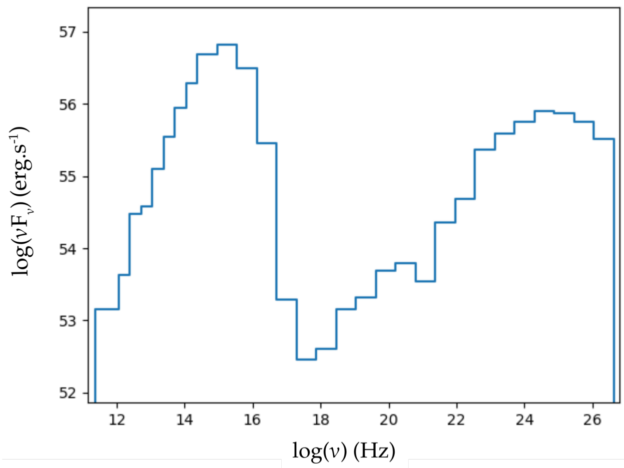

Figure 2: Figure 2: Spectral energy diagram obtained through MC simulations of a 16x16 cell region the beam of the RMHD simulation.

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